OPTIMIZATION OF SUBSONIC AERODYNAMIC SHAPE BY USING METAMODELING APPROACH

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Abstract: This paper presents an engineer oriented method for the optimization of subsonic aerodynamic shape by using the metamodeling approach. The method is based on using the commercial CAD and CFD software as well as the original code EDAOpt for design of experiments, approximation and optimization. The method is demonstrated by the solution of a test problem for an aerofoil subsonic shape optimization. The proposed method essentially decreases necessary computational resources.

Key words: optimization, metamodeling, aerodynamic shape.

1. INTRODUCTION

A continuous increasing of the energy resources cost determines the necessity to implement a careful optimization of the aerodynamic shape in the process of designing various objects. The most popular methods for aircraft design are the continuous reduced sequential quadratic programming [1], gradient methods [2], genetic algorithms [2, 3], etc. There are two main approaches [4, 5] for the aerodynamic shape parameterization: 1) by the coordinates of the nodal points [6, 7] and 2) by the coordinates of control points for approximation of shape by Bézier curves [8, 9] or piecewise polynomial functions, for example, nonuniform rational B-splines (NURBS) [10].

The optimization of shape is based on the mathematical model of the object. In order to assure possibilities of optimization in case of complex models, the most frequently used are the response surface method [11, 12]. In most cases of metamodel construction, polynomial functions, stochastic Kriging models, radial base functions or adaptive regression splines are used [5]. Polynomial models stand out due to ease of construction and speed of calculation, which is significant in case of global optimization tasks, which is what shape optimization is most frequently reduced to.

This paper presents an engineer oriented method for the optimization of subsonic aerodynamic shape by using the metamodeling technique and the second parameterization approach by NURBS. The form of the object is created using the commercial CAD software SolidWorks for 3D mechanical systems, the fluid dynamics calculation is carried out using CosmosFloworks (Further Floworks). The metamodeling and optimization tasks are solved using EDAOpt [12, 13] software developed in Riga TU.

2. METAMODELING METHOD FOR AERODYNAMIC SYSTEM OPTIMIZATION

The developed engineering methodology will be clarified by the example of a concrete task.

2.1. STEP 1 – DEVELOPMENT OF GEOMETRIC AND COMPUTATION MODEL

The object of calculation is a wing designed for testing of a subsonic wind
tunnel. Its cross-section does not change along its length and can be seen in figure 1, while the control point coordinates are given in table 1.

![An aerofoil geometry shown by NURBS](image)

The origin \( O \) and \( x \) axis of coordinates \( Oxy \) coincide with the chord of the aerofoil. The numeration of control points begins on the front edge and continues in order, first crossing the top of the wing to the back edge, and then going backwards along the underside of the wing to the front edge.

The calculation model has been created in the Floworks environment, based on the object’s geometrical model. Since the profile of the wing does not change along its length, the area of calculation is created using the object symmetry in order to minimize the calculations. During the execution of series of initial test calculations with the objective to achieve a stable Floworks result convergence, the following calculation area dimensions were chosen: \( x = [-98; 195] \), \( y = [-75; 82] \) and \( z = [-15; 15] \). The object of the calculation is an external flow task, with the assumption that the adiabatic walls of the solid body are smooth and with the following ambient conditions: \( V = 10 \text{ m/s} \); \( p = 101325 \text{ Pa} \); \( T = 293.2 \text{ K} \). The program analyzes a stationary flow task and allows laminar and turbulent flow types. The unstructured meshing with the elements of parallelepipeds were used, which in the vicinity of the air flow and solid body contact surface are additionally split. The meshing refinement level is 5.

The undisturbed air flow velocity is constant and the incidence angle in all calculations is 0. Additionally it is assumed that the object is fixed and the horizontal and vertical aerodynamical force components are calculated. The wing drag force \( F_x \) and lifting force \( F_y \) were chosen as Floworks global goals, and simultaneously designated as criterions of calculation convergence.

The optimal shape is found by varying control point \# 2 and \# 3 (see table 1) coordinates \( y_i \), which further figure as design variables, namely, \( X_1 \) – wing profile height \( y_i \) value in point \# 2 with coordinate \( x_2 = -15 \text{ mm} \), \( X_2 \) – wing profile height \( y_i \) value in point \# 3 with coordinate \( x_3 = -5 \text{ mm} \).

The number of FE for this specific task can reach up to 750 000 and the number of the necessary iterations varies between few hundred and a few thousand, and may even exceed 10 000 iterations. Therefore a single calculation on a 3.2 GHz Intel Pentium 4 computer may last even over 10 hours. In these cases it was necessary to limit ourselves to the satisfaction of only one convergence criterion \( F_x \).

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{No} & x_i & y_i & \text{No} & x_i & y_i \\
\hline
1 & -25 & 0 & 12 & 80 & 0 \\
2 & -15 & 7.5 & 13 & 75 & -0.75 \\
3 & -5 & 9.5 & 14 & 65 & -1.75 \\
4 & 5 & 10 & 15 & 55 & -3 \\
5 & 15 & 9.5 & 16 & 45 & -4.25 \\
6 & 25 & 8.5 & 17 & 35 & -5.5 \\
7 & 35 & 7.5 & 18 & 25 & -6.5 \\
8 & 45 & 6.5 & 19 & 15 & -7.0 \\
9 & 55 & 5 & 20 & 5 & -7.5 \\
10 & 65 & 3.5 & 21 & -5 & -7 \\
11 & 75 & 2 & 22 & -15 & -5.5 \\
\hline
\end{array}
\]

Table 1. Coordinates of the aerofoil control points

2.2. STEP 2 – DESIGN OF EXPERIMENTS AND NUMERICAL CALCULATIONS

Since the work amount for numerical experiments of the tasks of this type is considerable, it is important to choose designs that would make it possible to construct an adequate and qualitative model with a minimal number of experiments.
In these circumstances an adequate design of experiments must be used. This approach requires the use of the EDAOpt software, which allows to generate a great number of different designs with a fixed number of experiments, as well as original sequential experiment designs \cite{14}. In our case, a design of 16 experiments for two parameters $X_1$ and $X_2$ (see table 2), optimized according to V. Eglaj’s criterion \cite{12}, was chosen. The second column of this table shows the object’s cross-section shape for the current control point coordinate values.

The numerical experiments are executed as it is described in point 2.1. Geometric models of 16 objects were built using SolidWorks. Each of them is independently discretized with Floworks, and a corresponding mathematical model is obtained. The results of the solution of this model are summed up in the last two columns of table 2, where the maximal and minimal values obtained in the corresponding experiments are given in bold.

The values shown in table 2 correspond to the forces that act on the object only in area of calculation, that is, in order to obtain the total actual force, these values must be increased proportionally to the surface area of the object. Since the metamodel is used for optimization, it is sufficiently to operate with the relative values of these forces. It also should be noted that the force values given are averaged according to the 50 last iterations.

### 2.3. Step 3 – METAMODEL BUILDING FOR OBJECT OPTIMIZATION

The metamodels are created using the EDAOpt software, which allows one to build global and local Polynomial (up to third order) approximations. Various weighting functions (Gaussian, Tricube, Uniform, Triangle, Epanechnikov, Biweight, Triweight, Cosinus etc.) can be employed for the local approximations.
The 16 experimental points are represented on the response surfaces by squares, which in this case allow to visually judge the quality of the approximation. The quality of the obtained approximation can also be judged by analyzing a set of quantitative values given by EDAOpt. Approximations of all other metamodels of the given object can be obtained in a similar manner. Since the EDAOpt includes integrated optimization software, explicit expressions of the metamodel in the form of analytical equations are not necessary to the user.

2.4. STEP 4 - OPTIMIZATION AND ANALYSIS OF EXTREME

Employing metamodels, the admissible number of evaluations of criterion and constraints may be considerable and reach hundreds of thousands and even millions. Since their calculation requires significantly less time than the evaluation for the full model, it becomes possible to find the global extremes. The user may formulate various optimization tasks and quickly obtain solutions. We will minimize $F_x$, varying the parameters within the following limits: $-0.5 \leq X_1 \leq 11.5$ and $1.5 \leq X_2 \leq 13.5$, with the constraint that the lifting force may not be negative, that is, $F_y > 0$. Figure 4 shows the EDAOpt window with the optimum represented as a red point on the corresponding response surface.

The optimum found is close to the active constraint. Floworks calculation for the full model with obtained parameters converges for the $F_x$ while the $F_y$ oscillates around the zero value. In order to evaluate this optimum in detail, a sensitivity analysis is required. Further physical experiments in a wind tunnel are necessary to completely decide for the use of the given shape. It should be noted that formulation of the optimization task can be modified very easily and the results can be obtained almost instantly (for the given task, in a few seconds). If necessary, a stricter constraint can be put on $F_y$ and a new solution can be obtained.

3. OBTAINED RESULTS AND THEIR ANALYSIS

The obtained results are summed up in table 3, which is similar to table 2, except that the second column, in addition to the cross-section shapes, shows the calculated pressure distributions. The first 5 rows repeat the experiments carried out with Floworks, in which the extreme force values were obtained and the results corresponding to the initial shape. Further the table sums up the results obtained by Floworks for the full model in the optimum points located by EDAOpt.
Cross Section and Pressure Distribution

<table>
<thead>
<tr>
<th>#</th>
<th>X1 mm</th>
<th>X2 mm</th>
<th>Fx* 10^-2 [N]</th>
<th>Fy* 10^-2 [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>10.7</td>
<td>11.1</td>
<td>4.7</td>
<td>-8</td>
</tr>
<tr>
<td>10</td>
<td>3.5</td>
<td>3.9</td>
<td>0.35</td>
<td>-5</td>
</tr>
<tr>
<td>14</td>
<td>9.9</td>
<td>2.3</td>
<td>0.81</td>
<td>1.59</td>
</tr>
<tr>
<td>15</td>
<td>-0.5</td>
<td>8.7</td>
<td>0.56</td>
<td>-5.5</td>
</tr>
<tr>
<td>initial</td>
<td>7.5</td>
<td>9.5</td>
<td>0.45</td>
<td>0.41</td>
</tr>
<tr>
<td>o.</td>
<td>6.32</td>
<td>9.33</td>
<td>0.38</td>
<td>-0.28</td>
</tr>
</tbody>
</table>

Table 3. Extreme drag and lifting forces

Object shape has been located which reduces the drag force by 16%, while simultaneously reducing the lifting force. In fact, shape has been obtained for which lifting force oscillations occur, the physical nature of which can be ascertained only with the help of in-depth research, including experiments in a wind tunnel. The choice of this object was determined by the possibility to conveniently carry out the planned experiments in a wind tunnel. In principle, any other object in need of aerodynamical shape optimization can serve as a research object. The solved idealized test example must not be directly linked with wing design, but rather with the limited features of the CFD software employed, nevertheless in principle the methodology may be useful in employing other classical wing optimization methods as well.

4. CONCLUSIONS

The construction of metamodels using local approximation methods based on a small number of highly work-intensive experiments – the calculation of the full mathematical model and/or execution of natural experiments – is a promising approach in assuring the possibility to obtain optimal shapes of the object. The most work-intensive (from the point of view of computer time) are the operations involved in the second step of the approach, which signifies that it is crucially important to choose the most appropriate CFD software for the given physical problem. Since CFD software employs approximate numerical methods, the validation always must be carried out. The practical effectiveness of the method can be ascertained by performing wind tunnel tests and result validation, which is something that we have planned for the future. The question of the possibilities of application of this approach in cases of supersonic airflow has not been considered and remains open. The obtained initial results provide evidence that the developed methodology can be successfully used for the optimization of shape of subsonic aerodynamical objects and indisputably gives a significant economy of computational resources.

5. REFERENCES


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