A new approach to identification and optimization of airfoils by using the combinatorial-cyclic method

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Abstract

For the last several years the combinatorial-cyclic method of optimization has been validated and expanded to new areas of applications. Although coordinate measurement analysis still is the main area of applications, the method is becoming a useful and unique tool in design optimization, reverse engineering (parametric design included), and virtual engineering. The case study aerodynamics of airplane and turbine airfoils, and simulation of wind tunnels is very difficult and promising as well. To solve all problems arising in these areas, an extensive software within the integrated CAD/CAM /CAE system has been developed, written in GRIP (SIEMENS NX 3.8).

KEYWORDS: **airfoils**, **design optimization**, **combinatorial-cyclic method**

Introduction

Since we started to build airplanes, airfoils and even all droplike shapes, could not be defined by any curve known from the analytic geometry. Only in 1990's NURBS geometry has been fully formulated and it has given mathematical tools for handling a set of points, which in fact described airfoils so far.

From the very beginning of the study on fluid dynamics, the sets of points that define the shapes of bodies have not allowed the replacement of profile points by one curve, which by the adoption of the standard chord, could define the profiles for all other real chords. It is worth noting that all the airfoils consist of four different segments, each of these segments should be a separate curve with clearly defined beginning and end of the segment. Each of the four segments is determined from a given set of points, and the number of points can be very different – tens, hundreds, or even thousands.

There are well-defined geometric constraints for particular segments of the profile, resulting from research in aerodynamics and gas dynamics, and determining the approximate number of points required to define the optimal curve for each segment.

The key to accurately determine the location, orientation and length of the chord is a calculation of two extreme segments of the given profile, i.e. the leading edgeand trailing edge segments. The leading edge segment is always the curve of 2nd-degree, mostly circles, but ellipses, parabolas, and hyperbolas are also possible. The trailing edge segment is a line or the curve of 2nd-degree as in the previous edge.

To generalize algorithms for all airfoils, either airplane or turbine blades, in both segments the starting, ending, and midpoints are precisely calculated.

Therefore, the chord must be defined as the straight line joining the midpoint of the leading edge andthe midpoint of the trailing edge, and these points may not always be the extreme points of the profile.

When the starting point of the chordor the angular position of the chord are not exactly in line with the chord established from the set of points, e.g. joining the extreme points, then you need to transform the existing set of points to the coordinate system of the new chord. So far there were no such transformations, and errors arising from that, even more than 0.5 mm or 0.5 degree, could not be determined by the coordinate measurement. Now, by applying the method presented in this paper, it is no longer impossible.

After the corrected coordinate system has been established, upper and lower segments of the airfoil are optimized to fit to the transformed set of points. To optimize the airfoil as a whole (four segments), the combinatorial-cyclic method is necessary.

The airfoil as the optimal curve can be presented in the NURBS geometry definition:

nurbs1=bcurve/fit, p(1..n),toler,t,degree,d

where: p, t, d– obtained from the optimization process (p– selected points, e.g.15 to 25 points;t– max.distance between the selected points and curve, d – degree of the upper and lower segments of the airfoil – mostly 3.

The method used to optimize the profile curve can be extended to solid bodies of an airplane wing, stabilizer, and fuselage. Also, turbine blades, compressor blades etc. areoptimized by this method, but, of course, the software for an automatic generation of geometric models must be developed.

The optimal airfoil with the mean chord length (e.g. 100 mm, 1000 mm or any other) are then parameterized. The main aim of parameterization is establishing the optimal mathematical formula for interrelationships between characteristics of the airfoil and parameters, e.g. c_l or c_d as a function of p(1 … n). It is possible, to read parameters from the airfoil and, inversely, to build the airfoil from parameters. The airfoils can be divided into classes, depending on the specific properties of airfoils or standard length of the chord. Usually, for increasing the accuracy of the calculation of aerodynamic characteristics, e.g. c_l, c_d for all airfoils resulting from the scaling the basic airfoil with a mean chord length, the database should include airfoils with 3 levels of the chord length, e.g. 1000–1000/2, 1000, 1000 + 1000/2. Such a database for each class of airfoils allows the determination of corrections to aerodynamic characteristics for the airfoils created by scaling the airfoil available in the database, it means for airfoils that are resized.

Of course, the complete and reliable database enables to develop the software simulating a wind tunnel. Instead of manufacturing a physical model of airfoil shape for a wind tunnel,it is possible to predict c_d and c_l from airfoil parameters.

The method has been made feasible, because of a new generation of computers (lately 32 GB RAM, 2.5 GHz processors) and programming tools within the integrated CAD/CAM/CAE system (Siemens NX5..8 GRIP). To carry out a comparative analysis of aerodynamics between military airplanes MIG-29, F-16, and passenger airliners A-380, B-787, the presented method has been used. The database has been completed in part from the available documentation, partly by reverse engineering techniques,and partly through the wind tunnel tests. This validates a software-based approach to the problem solving, but also forces the modification and the further development of the method.

In summary, the new approach lies in the fact that to the current knowledge on the airfoils the new mathematical tools has been introduced, which enable to accurately define the airfoil by optimizing the segment curves in relation to a set of points, to determine the aerodynamic characteristics of the airfoil, and to extend the characteristics on all airfoil sizes in a given range.

Combinatorial-cyclic method of optimization

Combinatorics and iterative computational processes have been used for centuries, but the effectiveness of these methods of determining the extreme values was very limited, especially with more optimization variables and the occurrence of multiple local extrema. Analysis of the results of each iteration runs was too time-consuming, even with the use of computer systems. A design optimization by using these methods has been impossible in practice.

Only a uniting four types of software gave base to devise a method that enables efficient solving of problems, previously unsolvable. These four types of software are:

- Fortran-like loops for 10 to 15 optimization variables, where 1 cycle is the run for one set of input data;
- artificial intelligence program, responsible for preparing a new set of input data for each cycle, for the differentiation between a global optimum and local optima, and for the introduction of suitable input combinations, depending on whether the target mode is deterministic or probabilistic;
- system program cleaning a RAM memory, reserved for the CAD/CAM/CAE system;
- programs that generate hundreds and even thousands of geometric models, required by the objective function defined, and according to the rules of the CAD/CAM/CAE system.

A decisive factor in measuring computer capabilities for design optimization is a RAM memory, and resulting from that the required frequency of RAM cleaning. Since 2003 (the year of publishing the comb._cyc. method) [1], the RAM memory in workstations, PCs and notebooks has increased from 4 GB to 64 GB and it means that time effectiveness of combinatorial-cyclic method, extended by artificial intelligence techniques, has increased about 10 times.

The next step will be a possibility to fully apply the multiprocessing, what, in turn, may increase time-effectiveness by 10 to 500 times.

For the last several years, the combinatorial-cyclic method of optimization has been validated and expanded to new areas of applications. Although coordinate measurement analysis still is the main area of applications, the method is becoming a useful and unique tool in design optimization, reverse engineering (parametric design included), and virtual engineering.

Below, one of the most difficult case study: airfoils of airplanes, turbine blades, etc., and building the data base for simulation of wind tunnels.

The structure of subprograms is fit to different area of applications, since one subprogram is treated as target-oriented and defining the objective function as well as selecting either deterministic model or artificial intelligence model. There has been gathered a considerable experience in the following main areas of applications:

- Analysis of all errors in manufacturing processes, even on the most complex surfaces (e.g. airplanes, turbines, propellers, car bodies etc.), moreover, on each stage of CAD/CAM technology; eliminating the necessity of a precise set-up of the part being measured on a CMM table or for scanning system; verifying the accuracy of CMM itself and applied software. The specialized software is of a great importance for effective calculation of dimensional deviations between the virtual product model and the part machined, defined by a cloud of points (even more than 2 million).
- Design optimization, according to required accuracy of location and orientation of principal axes of inertia or other design objective functions, e.g. minimizing the deviation between principal axis and axis of rotation; optimization of parametric design, where parameters are optimization variables; it enables us to effectively apply reverse engineering techniques (max. number of optimization variables=15).
- Establishing the optimal mathematical formula for interrelationships among variables, based on experimental data or parametric design data; it works as an extension to multiple regression analysis not requiring the linearity. Usually, we can consider additionally 2nd or 3rd degree, power or exponential equations.
- Solving the equation systems, linear and non-linear, particularly, where the number of unknowns is less than number of equations; mostly applied to analytically defined surfaces (e.g. sphere, plane, cylinder, cone, ellipsoid, etc.). The method identifies these surfaces and solid bodies with high accuracy from a cloud of points, obtained from coordinate measuring systems.

To achieve higher geometric accuracy of complex shapes, airfoil shapes included, and overall increase in surface quality it is necessary to take full advantage of capabilities available in integrated CAD/CAM/CAE systems as well as in a new generation of CNC production equipment and coordinate measuring machines. Due to a large number of points (500 to 100 000, and for wings and fuselages more than 1 million), obtained from scanning and digitizing measurements, it is only recently possible to run the appropriate, specialized software. To find a global optimum in the location and orientation of the set of points (cloud of points) in relation to the geometric model, the presented method has been applied. A combinatorial-cyclic method is, in fact, an reliable multivariable optimization method based on either deterministic models or selected neural network techniques.

The approach enables:

- to analyze all errors in manufacturing processes, even on the most complex surfaces;
- to effectively apply reverse engineering techniques ,what is particularly important for airplane shapes;
- to identify all sources of errors in CAD/CAM/CAE technology;
- (d) to eliminate the necessity of a precise set-up of the measured part on CMMs or other measuring systems;
- to identify a global optimum, among many local optima.

A geometric model of surface concerned, or rather a solid body, is a base for any distance calculation along normals between points and the surface. It should be noted, that even in the same CAD module using the same point set for available various curve and surface definitions (a cubic spline, Bezier curve, B-spline, NURBS curves and surfaces), the different surfaces may be built. The differences arising from applying the different curves are not negligible and for inspecting the surfaces by a CMM, the geometric model used for CNC part programming should be known.

Due to a large number of points obtained from scanning measurements, it is only recently possible to run the appropriate, specialized software. Still, it can take several hours, even when workstations or PCs have more than 4 GB RAM and 2.5 GHz.

Therefore, the important feature of the programs is the capability of selecting the points from a large data file, keeping almost the same accuracy of the analysis. This is a first layer in an artificial network approach.

Also, the number of combinations can be reduced and it is a second layer in this approach. 10% of all points and combinations can enable to obtain results with the difference below 4% in relation to results from the analysis based on the full point set and a deterministic model.

Nevertheless, the most important feature of the programs is an effective, convergent iterative method, searching for optimum values of selected variables with accuracy required. These variables are either coordinates for an origin and angles for an axis orientation (in an analysis of surface errors) or dimensions of the geometric model (in reverse engineering).

Optimum variable values are searched according to the established objective function, which, usually but not necessarily, is a sum of squares of distances between points and surfaces. It must be pointed out, that for an reverse engineering applications of the method, the prerequisite is to develop a specialized subsystem for an automated design of the geometric model of the object. For the other applications this subsystem is preferable to an CAD interactive model, but not necessary.

Developed procedures, based on neural network techniques, used in the optimization model of both deterministic and probabilistic modes, are mainly defined by three important values:

- n - the number of points from coordinate measurements (the first layer in a neural network);
- m – the space dimension (the number of variables, optimal values of which are searched);
- k – the number of levels for each variable (k=3,5,7,9,11,...), i.e. dimensionless coded values of variables (e.g.:k=3 gives coded values: –1,0, 1; k=5 gives coded values: –2,–1,0,1, 2 etc.).

$N_c = k^m$ – the number of combinations, e.g.:

$11^2 = 121$

$3^{10} = 59\ 049$

$3^5 = 243$ (mostly used in a practical analysis of surface errors)

$11^5 = 161\ 051$

$11^{10} = 25\ 937\ 424601$ (a difficult problem even for supercomputers).

N_c is the size of the second layer in a neural network.

Increments in a program loop d$v(j)$ and code values $i_v(j)$ define boundaries (ranges) and real values of variables:

$$v(j)_i = v(j)_0 + (2\, i_v(j)\, \mathrm{d}v(j)/(k-1))$$

e.g.:

if $v(1)_0$= 100 mm, d$v(1)$=2 mm, k=3

then $v(1)_{-1}$= 100 –2 =98 mm, $v(1)_1$= 100 +2 =102 mm

if k=5

then $v(1)_{-2}$= 100 –2 =98 mm, $v(1)_{-1}$=100 – 1 = 99 mm;
$v(1)_1$= 100 +1 =101 mm, $v(1)_2$= 100 +2 = 102 mm

In general, k-level m-dimensional space is determined by a matrix, where: m- the number of columns, k^m – the number of rows. The number of rows defines an information capacity as well. The units used for variables: m, mm, mm, nm, degrees, 1/1000 of degree. Generally, the objective function of the optimization method is to minimize geometric deviations between a virtual product, represented by a CAD model of the product, and a real product after manufacturing, represented by points from measuring systems. It must again be pointed out, that tasks of reverse engineering require software-based automatic redefinitions of the CAD model, according to changing design variables. Usually, transformation problems can be separated from reverse engineering problems and it makes the difficult objective as a feasible one.

There are criteria of an accuracy estimation of curves and surfaces, which can be used as the objective function (mostly a standard deviation):

$$s = \sqrt{\frac{\sum_{i=1}^{i=n} (d(i))^2}{n}}$$

$$t_{out} = \frac{\sum_{i=1}^{i=nout} + d(i)}{nout}$$

$$t_{in} = \frac{\sum_{i=1}^{ii=nin} - d(i)}{nin}$$

where: σ– standard deviation; t_{out}, t_{in} – average upper and lower deviation; $+d(i)$, $-d(i)$ – outside and inside distances of points along normals; $nout+nin= n$ (the number of points).

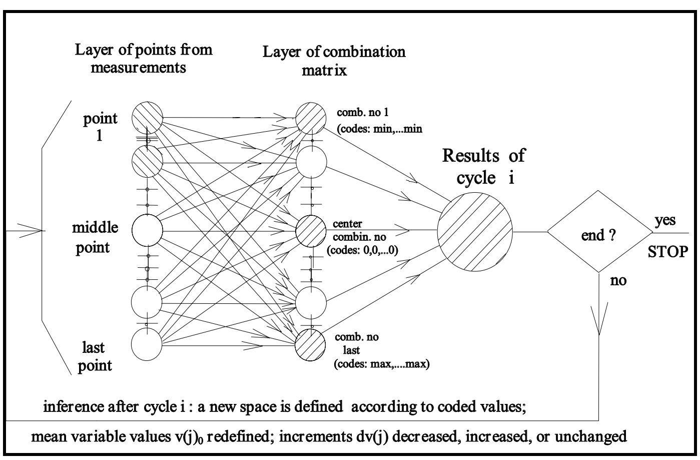

Fig. 1. *Combinatorial-cyclic optimization method presented in artificial neural network concept. One-directional two layers supported by evolutionary optimization algorithms; hatched elements of points and combinations are activated even in the probabilistic mode, not in the deterministic mode only*

The presented method has been validated, verified and tested on analytic shapes and NURBS surfaces as car body dies (including elimination of springback errors in sheet metals), a glider wing and airplane wings, a parabolic antenna (including elimination of springback errors in sheet metals), an airplane fuselage (military airplanes and passenger airliners), an airscrew, an yacht hull, hip joint prostheses, gears etc. The dedicated software has been developed within the frame of the integrated CAD/CAM/CAE system SIEMENS UGS NX (GRIP).

Speaking from experience gathered in the area of the method applications in design and manufacture, there are two main points in optimization methods: a convergence of iterations and globality of the optimal solution. The difficulties at these points seem to be insurmountable in terms of general mathematical formulas, but it is worthy to notice, that human brain is usually able to find an optimal solution after considering all aspects of the problem. Therefore, the combinatorial-cyclic method of optimization is embedded in an artificial intelligence techniques, including a neural network approach, where logical inference is based on designer's and manufacturer's knowledge. It is necessary, because in some cases a CAD model or CAM-NC programming are interrelated with optimization algorithms. As a result, a convergence and globality problems has been overcome, but it has been proven in the same way as in other reliable engineering software; a Coordinate Measuring Machine has been simulated and received points from the CAD model can be treated as an input to the optimization method.

Of course, the point set (cloud of points) has a predetermined standard deviation, *x*-, *y*-, *z*-, α-, β-errors, points with maximal (+) and minimal (–) errors, and incorrect geometric parameters. If these data will be repeated as results from the method, we can assume that the method is correct. And it has been tested in 25–30 difficult cases. Simply put, it is a good way to validate the method; if a set of points is taken from the CAD model and some of these points will be given the errors deliberately, the method should discover these points and their errors.

Absolute proof would be, when we divide m-dimensional space on elements equal to required accuracy, and a computer power is sufficient. Still it is a long way for computers. The simplest element in the *m*-dimensional space is a 3-level element and the entire space can be divided on $((k - 1)/2)^m$ subspaces, all of which have the same sizes as space concerned, (in dimensionless codes), but with dislocated subspace centers. In deterministic mode, one cycle includes calculation of the objective function for all points from measurements with all combinations of the variable values, and it means that in 5-dimensional space the 11-level calculation requires 660 times more computational power than the 3-level calculation.

Description of the optimization method presented in the chapter uses the notions and terms not found in aerodynamics and apparently does not seem to fit the theme. Yeah maybe, but even rough outline is helpful in understanding the concepts presented briefly in the paper; broader presentation the optimization method [1].

Identification and optimization of airfoils

The combinatorial-cyclic method of optimization has mostly been used for solving the problems within the aircraft industry. Successes of CFD software encourage to a new approach to aerodynamic research, particularly, to problems hitherto unsolved.

In the paper have been presented the algorithmic approach to achieve three main goals:

- parametric design ; the simplest airfoil – 4 parameters,the complex airfoil – 9 parameters;
- establishing the interrelationships c_d=f(p(1..9)), c_l=f(p(1..9)) etc., where: c_d –coefficient of drag, c_l –coefficient of lift, p(1..9) – parameters of an airfoil;
- building the data base for a specified class of airfoils; to fully utilize possibilities of the method the length of chord can be arbitrary (not 1 or 100 only), with 3 levels of the chord length for more complex cases, e.g. $l_c – l_c/2$, l_c, $l_c – l_c/2$, where l_c – mean chord length;
- generalization to all airfoils, i.e. of wings, stabilizers, longitudinal section of an aircraft fuselages, turbine blades, compressor blades, airscrews etc.

After the goals have been achieved we can use it in both ways, either reading the c_d and c_l for a given airfoil or designing the airfoil for a given c_d and c_l.

The generalization of the calculations for all profiles must meet these basic conditions, which are given in the chapter Introduction (above), this is a precise calculation of the airfoil chord, leading and trailing edges from a given set of points.

Before testing in a wind tunnel, you must measure the accuracy with which the physical model is CNC machined in comparison with the designed CAD model, and in fact with CAD solid body. It is especially important when the geometric CAD model has been made in other CAD/CAM system than the CNC program. What is a generalization of the geometric identification of all airfoils in use, is presented graphically on the example of an airplane airfoil and the airfoil of a turbine blade (fig. 2).

The main differences are leading and trailing edges, which in turn have a significant impact on the chord. A geometrically accurate airfoil, optimized against a set of points, is an essential condition for the transition to solve other tasks, generalized by the dedicated software.

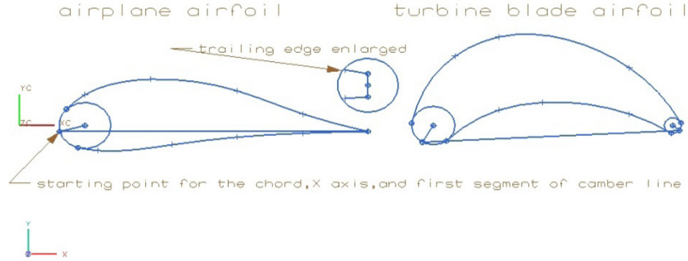

Fig. 2. *Accurate calculation of leading and trailing edges of the wing airfoil and of the turbine blade airfoil. As a result, we may adjust the length and position of the chord, what enables to transform points defining the airfoil. Then the airfoil as a Nurbs curve can be optimized in relation to the transformed set of points. The middle point and two boundary points in edge curves or edge lines are of great importance in the presented concept. The figure has been generated by the optimization program from a cloud of points (hundreds of points), as a file1.jpg*

It is recognized that almost always when we get an airfoil as a cloud of points, we have no certain information about the precision with which the *X*-axis of measurement system coincides with the airfoil chord.

To indicate the validity of the problem of airfoil accuracy, the most important aspects have already been presented in the Introduction above. Circles, ellipses, parabolas or hyperbolas are computed from 15 to 30 points taken from the area around both edges.

The results of iterative computations with the ever decreasing number of points are as shown in the printout after each run with a new number of points from eg.30 to 5. Therefore, to minimum 5, because the curves of second degree are defined as general conics (fig.3).

Similarly, it can also be shown the optimization of the airfoil as one NURBS curve, linking together all four segments, i.e. segments of leading and trailing edges with upper and lower segments.

The results of combinatorial-cyclic method are printed in fig.4. Precise identification of the airfoil geometry means that the geometrical model requires only the development of a tool path for CNC milling machines withn 3- or 5-axis. The presented sequencing gives a very large guarantee, that we can achieve a high accuracy and repeatability, assuming that we proceed within the integrated system.

```
=================================================================
General conic: CIRCLE(0,1),ELLIPSE(1),PARABOLA(3),HYPERBOLA(2)
A*x**2 + B*x*y + C*y**2 + D*x + E*y + F = 0
------------------------------ ncall=  4
n1= 8, n2= 5, n3= 1 n4=15, n5=12
Conic index (as above): ehp=1, first point p( 8)
ellipse center:  149.7212,  26.0472,    .0000
   semimajor:  150.0000
   semiminor:  149.8732
   tilt angle:   10.0000
   start angle:  211.3381
   end angle:  542.8950
   start point:   19.8343, -51.8256,    .0000
   end point:   -2.0562,  18.4729,    .0000
standard deviation for all points p (8..12): sigma=  0.13776
================================ optimum after ncall=  4
OPTIMUM GCONIC-CURVE:p( 8),p( 5),p( 1),p(15),p(12);  sigma_min=  0.13776
Remove all points below and insert the middle, and 2 boundary points
p( 8)=POINT/  -2.0562,  18.4729,  .0000
p( 5)=POINT/   5.8911,  73.4382,  .0000
p( 1)=POINT/  46.8690, 135.1525,  .0000
p(15)=POINT/  57.6299, -92.7142,  .0000
p(12)=POINT/  19.8343, -51.8256,  .0000
======== END OF GCONIC_CURVE OPTIMIZATION FOR THE AIRFOIL ==========
```

Fig. 3. Printout from the program showing the outline of algorithmization for the general conic optimization, i.e. for both edges of the airfoil. The middle point and two boundary points (tangency points) are also calculated in the program

```
========================================================
The required accuracies have been achieved: delt(1..2)<accur(1..2)
========================================================
Optimal combination after cycle:  20
  20 : TOLER=vsrch(1)= .07690 mm; DEGREE=3; points for NURBS=ptm2
--------------------------------------------------
Points -popt(..)- for the optimal NURBS curve, chosen from       88 points
popt(  1): x=  1250.000 y=      .938 z=      .000
popt(  2): x=  1229.092 y=     6.365 z=      .000
.........................................................................
popt( 18): x=  1225.478 y=    -3.738 z=      .000
popt( 19): x=  1250.000 y=     -.938 z=      .000
==============================================================
 AIRFOIL ACCORDING TO NACA (in parenthesis in „mm")
==============================================================
Chord length: lc=1250.000 mm
------------------------------------------------------------
  X  (%)        Y_upper(%) Y lower(%)  Thickness(%)
------------------------------------------------------------
 1      0.000         0.000          0.000       0.000
    (    .000)    (   .000)     (   .000)    ( 0.000)
 2      5.000         5.074         -3.717       8.791
    (  62.500)    (  63.421)    ( -46.469)  ( 109.890)
 ...................................................................................
20    95.000         1.295          -.638        1.933
    (1187.500)    (  16.188)    (  -7.969)  (  24.158)
21    100.000        0.000          0.000       0.000
    (1250.000)      (0.000)       (0.000)     (0.000)

           FINAL RESULTS OF OPTIMIZATION
==========================================================
------------  ANALYSIS OF ERRORS ------------
The number of points exceeding +/-st.dev.limits:     16 ( 18.18 % of    88)
The number of points outside (above    .5779374):     8 (  9.09 % of    88)
The number of points inside (below    -.5779374):     8 (  9.09 % of    88)
The standard deviation: sigma=       .577937443   <<<<<<<<<<<<
The mean upper deviation (outside distances):    .2525577 (     58 points)
The mean lower deviation (inside distances):    -.4677266 (     30 points)
The number of errors exceeding 3*st.dev.:    2 (  2.27 % of    88)
The number of uncorrected errors,exceeding 3*st.dev.:   0 (  .00 % of    88)
----------
          OUTSIDE AND INSIDE ERRORS
          ==========================
Ten maximum outside distances:
ptm(   52): x=    70.7263 y=   -50.6200 z=      .0000   dist=    0.897397608
ptm(   51): x=    43.3901 y=   -41.4970 z=      .0000   dist=    0.763446347
....................................
Ten minimum inside distances:
ptm(   58): x=   196.8497 y=   -68.3165 z=      .0000   dist=   -1.115817982
ptm(   57): x=   173.1988 y=   -66.6125 z=      .0000   dist=   -0.803037321
....................................
======= END OF FINAL RESULTS =============
```

Fig. 4. *Wing airfoil optimization using the combinatorial-cyclic method. Results read from the printout define the Nurbs curve: nurbs_air=BCURVE/FIT,popt(1..19),TOLER,0.0769, DEGREE,3. Of course, the formula is from the integrated CAD/CAM/CAE system library. The airfoil measurement made by a laser measurement system*

Parametric Design of Airfoils and Data Base

The parameters in the design within the CAD system mean geometric entity dimensions, less physical quantities, that allow the automatic generation of new variants of the design, which in turn allows the design optimization. But in the case of airfoils described parameters (fig. 5) does not automatically generate more and more other airfoils, but are introduced for another purpose, i.e. to find such variables, that c_l, c_d , and other characteristics of the airfoil can be treated as f(*v*(1..n.), where *v*(1..n) are optimization variables selected from parameters *p*(1..*k*) after stepwise multiple regression analysis. The rules of building a NACA airfoil are faster, and can be used to build about 20 airfoils, but the c_l and c_d must already be known, or perform testing in a wind tunnel. Such a data base of 20 airfoils can be used as a starter data at the beginning of work on this software, or to check the software used.

In the case described in the paper it is assumed that the starting data base are 10 cross-sections of the wing F-16, and 10 cross-sections of the wing MiG-29, because, in general, airfoils data are already known. It can be very useful for a comparative analysis of airplane aerodynamics. NACA airfoils and others imply that c_l and c_d does not depend on the scaling, nevertheless, database must facilitate the introduction of corrections if the impact of scaling occurs, which is inevitable when the scale is too large. Therefore, in some cases, in the database must be the same airfoils but at the three levels of the chord length, i.e. mean chord l_c , and two chords $l_c + l_c/2$, $l_c - l_c/2$.

Design parameters for airfoils (fig.5) have been used for airfoils of wings, turbine blades, propellers, although, shapes are meaningfully different.

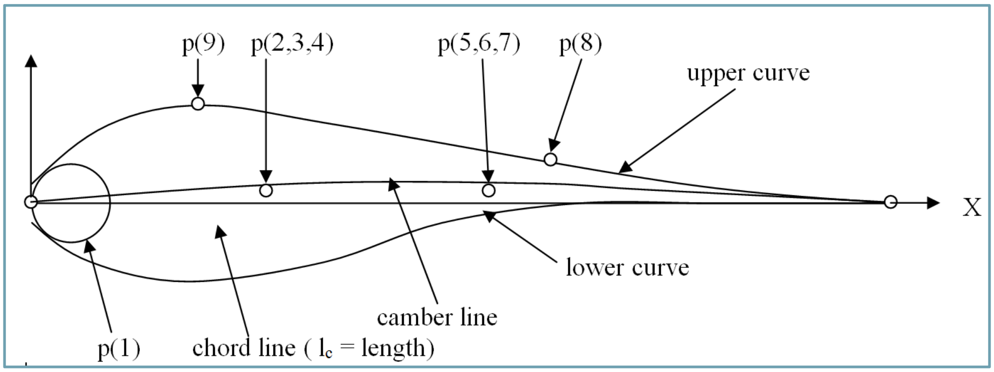

Fig. 5. *Parametric design of airfoils; there are 3 scalars and 4 points as the parameters;the real dimensions of an airfoil can always be scaled to any other chord length (50,100,1000etc.): p(1) – radius of circle on leading edge;p(2) – area bounded by an airfoil;p(3,4) – x,y of the center of the area p(2);p(5) – area bounded by a camber line and chord line; p(6,7) –x,y of the center of the area p(5); p(8) – x of the inflection point on upper curve; p(9) – y of the point of maximum thicknesson upper curve*

Here are the steps in the software, which as dedicated programs cover all problems.

- **Step1**: To find 10 or less airfoils, covering the specified range of applications, with given c_d and c_l. It is an initial data base, largely extended after the goals have been achieved. The required airfoils can be obtained by three ways: reverse engineering techniques, NACA airfoils, or from wind tunnel tests. The design parameters are calculated from an airfoil, which, at first, must be added with accurate camber and chord lines. Establishing the start and end points of the chord line (*X* axis) is a key factor for the accuracy of results.
- **Step2**: The system of equations with *n* variables and unlimited number of lines (minimum=*n*), where, one line means one airfoil with given c_d and c_l. To solve the problem we use two phases:
  a) stepwise multiple regression analysis,
  b) combinatorial-cyclic method of optimization.

From (a) we find out which parameter *p*(1..9)can be treated as optimization variables *v*(1..*n*), it is after correlation analysis. Also we obtain linear equations of the form:

$$c_d = d1*p(1)+d2*p(2)+d3*p(3)+d4*p(4)+d5*p(5)+ \\ + d6*p(6)+d7*p(7)+d8*p(8)+d9*p(9)$$

$$c_l=l1*p(1)+l2*p(2)+l3*p(3)+l4*p(4)+l5*p(5)+$$
$$+l6*p(6)+l7*p(7)+l8*p(8)+l9*p(9)$$

If n=4, we obtain:

$$c_d=d1*v(1)+d2*v(2)+d3*v(3)+d4*v(4)$$

$$c_l=l1*v(1)+l2*v(2)+l3*v(3)+l4*v(4)$$

From(b) we obtain the above equations, but it is possible to extent equations to any other mathematical form. The standard deviation is the measure of accuracy, and for the optimal mathematical form:

st.dev.= minimum from among other searched forms

After the goals have been achieved we can use it in both ways, either reading the c_d and c_l for a given airfoil or designing the airfoil for a given c_d and c_l.

- **Step3**: In some way, this step is reversed step1. We know, from our data base, the parameters which give specific values for c_d and c_l and want to build the airfoil. As a result we obtain the airfoil, described in a required form, in NACA form as well.

Of course, it is also the way how to develop the software simulating a wind tunnel. Instead of manufacturing a physical model of airfoil shape for a wind tunnel, it is possible to predict c_d and c_l from airfoil parameters.

The method has been made feasible, because of a new generation of computers (4 GB RAM, 2.5 GHz processors) and programming tools within the integrated CAD/CAM/CAE system (Siemens NX5..8- GRIP).

Printouts from the programs covering Step2 and Step3 have not been put in the paper, because there is not enough space available and this software is still being verified, tested, and modified.

References

Ziętarski S. AI-based optimization method for the analysis of coordinate measurements within integrated CAD/CAM/CAE systems. Computer Aided Production Engineering ,CAPE 2003. Professional Engineering Publishing Limited,London and Bury St Edmonds, UK, 2003.