Proceedings in MANUFACTURING SYSTEMS

Proceedings in Manufacturing Systems, Volume 11, Issue 4, 2016, 175-182 ISSN 2067-9238

AIRFOIL GEOMETRIC INSPECTION OPTIMIZATION FOR CONTACT MEASURING PROBES

Vidosav D. MAJSTOROVIĆ[1], Srdjan P. ŽIVKOVIĆ[2,*]

[1)] Prof. Dr., Mechanical Engineering Faculty, Laboratory for Production Metrology and TQM, Belgrade, Serbia
[2)] Dr., Head of Section, Military Technical Institute, Coordinate Metrology Lab, Belgrade, Serbia

Abstract: *This paper presents optimization of airfoil measurements on coordinate measuring machines with contact type probes. The considered optimization aims to minimize the necessary time for airfoil coordinate inspection. Minimizing the time for finishing of metrological task is obtained by minimizing the number of airfoil control points necessary for coordinate inspections. This mode directly minimized the costs of the measuring operation but also indirect costs of machining operation. Milling machines are waiting for the next machining operations during of airfoils measurement at CMM. The minimum number of points for airfoil coordinate inspections obtained from the condition that all deviation of applied interpolation curve to wing surface are within the defined tolerance. Selected criteria are accuracy of CMM for measurements length (airfoil chord) increased by the value of the CMM measurement uncertainty. Developed and presented method was successfully applied on several international projects.*

Key words: *coordinate measuring machines, wind tunnel models, wing, airfoil, accuracy.*

1. INTRODUCTION

According to ISO/TS 17450, all ideal features belong to one of the seven invariance classes: complex, prismatic, revolute, helical, cylindrical, planar, and spherical. Complex geometrical features have no invariance degree. Freeform surfaces, also called sculptured surfaces, may be classified as complex geometrical features. Freeform surfaces are widely used in the industry. The reasons for the implementation are functional and aesthetic: automotive and aerospace industries, household appliances, and others [1].

Turbine blades and aircraft wings are defined using very different airfoils. In some cases, a very high accuracy of the aerodynamic surfaces was requested. The accuracy of airfoils (blades, impellers, wings, rudder, flaps, slats, aileron, and canards) has a very large impact on aerodynamic performance. Airfoil manufacturing errors have great impact on performance in the subsonic [3], transonic [4] and supersonic areas.

Wind tunnel tests are experimental support for the development and design of new aircraft, used to verify the theoretical calculations. Models for wind tunnel tests are a special class of aerodynamic surfaces [1]. The assumption of similarity is the starting point for all experimental aerodynamics tests. The most important requirement is the geometric similarity [2] between wind tunnel model and prototype airplane. Geometric similarity can be checked only by using specialize developed method of coordinate metrology [1].

* Corresponding author: Ratka Resanovića 1, 11030 Belgrade
Tel.: +381 66 8721403;
Fax: +381 11 2508474;
E-mail addresses: *vidosav.majstorovic@sbb.rs* (V. Majstorović), *srdjan.vti@gmail.com* (S. Živković)

2. MAIN OBJECTIVES OPTIMIZATION

Minimizing the time coordinate inspection shall not affect the measurement accuracy and reliability of the results. It is necessary to achieve the projected quality of the completed model aircraft in the shortest possible time interval for the current technical—technological equipment. Total time and final quality are inextricably linked wind tunnel model categories.

Producing the wind tunnel models, according to the required (designed) quality and within the contract defined end time, defined mission and goals of management of the manufacturing process wind tunnel models [6]:

- defining the flow chart of manufacturing process; identifying critical operations and activities;
- minimizing the time coordinate inspections of model elements between machining operations;
- providing management of the additional machining material for all types of machining operations as follow;
- defining methods for identifying quality parameters related to the spatial position and the mutual relations of the elements of the wind tunnel models

Inspection of wind tunnel model's geometry has two aspects: first is the final inspection prior to wind tunnel testing and second aspect is series of geometric inspection during the manufacturing process.

CMM report is final evidence of model's quality and geometric similarity between wind tunnel model and prototype airplane.

Coordinate inspections between machining operations must provide manufacturing without defects and rejec tion. Coordinate inspection is key-factor to managing manufacturing process of aircraft models to achieve planned quality.

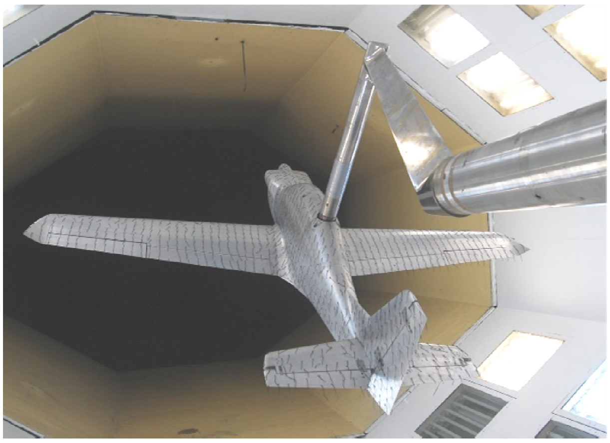

Fig. 1. Model of airplane LASTA-2 (scaled 1:5) in large subsonic wind tunnel T-35 (MTI Belgrade).

Both aspects of the coordinate inspections of aircraft models require the solution of the problems of access to comprehensive.

This paper presents optimization of airfoil measurements on coordinate measuring machines with contact type probes. The considered optimization aims to minimize the time needed to coordinate inspection. Minimizing the time for finishing of metrological task is obtained by minimizing the number of points of airfoil coordinate inspections. This mode directly through minimized the costs of the measuring operation but also indirect costs of machining operation. Milling machines are waiting for the next machining operations during of airfoil measurement at CMM.

3. WIND TUNNEL MODEL ACCURACY

Size of wind tunnel test section dictates the size of the wind tunnel model. Most of the wind tunnel models are scaled in relation to the prototype aircraft. In rare cases wind tunnel models are not scaled.
Regardless of whether it is scaled or non-scaled, geometric accuracy of wind tunnel models is very high. These are aerodynamics laboratory tests and it is reason highly required accuracy. For wind tunnel models are defined two types of tolerances [5]:

- Aerodynamic tolerances are related only to the aerodynamic performance of the aircraft model.
- Technical tolerances provide functionality and validity of all connections in the model and the carrier (sting).

The wind tunnel model is scaled but aerodynamic tolerances are not obtained by simple scaling prototype airplane tolerances. Tolerances of wind tunnel models are much narrower. Inverse is also true: prototype airplane tolerances are not a simple multiplication of wind tunnel model tolerances. They are much wider.

Aerodynamic tolerances of model shown in Fig. 1 are a good explanation of prior consideration. For model whose wingspan nearly 2m aerodynamic tolerances listed below [5]:

- overall length 1593± 0.50 mm;
- fuselage profile ± 0.25 mm;
- wing span 1940± 0.20 mm;
- wing root chord 358± 0.10 mm;
- wing tip chord 215± 0.10 mm;
- wing setting angle +2º ± 0.10º;
- wing dihedral angle +3º± 0.10º;
- wing tip chord twisting +3,5º± 0.05º;
- airfoil (NACA 63_2-415) deviation ± 0.05 mm;
- airfoil thickness ± 0.10 mm;
- WRP position ± 0.20 mm;
- tail-WRP angular relation ± 0.10º.

2.1. Manufacturing accuracy in the world's leading companies

Some of respectable world companies give web presentation manufacturing tolerances for wind tunnel models. Tolerances of aerodynamics surfaces for wind tunnel models in Russian CAGI (*Central Aero-hydrodynamics Institute*) are 0.04 mm. British ARA (*Aircraft Research Association*) declares accuracy for wind tunnel models are ± 0.025 mm "where required". Dutch NLR (*Nationaal Luchten Ruimtevaart Laboratorium*) declares form accuracy < 0.05 mm and angular accuracy < 0.1 degree for wind tunnel models. German DEHARDE (*Maschinenbau*) declares "Contour tolerance better than ± 0.015 mm" for wind tunnel models which they produce. French ONERA (*Office National d'Etudes et de Recherches Aérospatiales*) and NASA (*National Aeronautics and Space Administration*) are not declaring in public manufacturing accuracy of wind tunnel models. Manufacturing accuracy of the wind tunnel models shows that the MTI technological capabilities are very close to those of the above mentioned institutions.

4. AERONAUTICAL SURFACE MACHINING ERRORS

Manufacturing a wing for wind tunnel models is the best way to explain complexity of aerodynamics surfaces manufacturing process. Wing is made of prismatic work piece by first shaped to their top view. Then alternate cutting upper and lower side of the wings to get more repeated operations required aerodynamic shapes [5]. The required form must always be made in very narrow tolerances of shape. Among each of the cutting operations, it is necessary to measure the geometry of the wing.

Airfoils are defined in tables and classified using 4 and 5 digits. Upper and lower side of the airfoil is defined by the control points for the range of 0 to 100%, Fig. 2. Airfoil shown on Fig. 2 is used for wing design of aircraft LASTA, shown on Fig. 1.

The flow chart of the wing manufacturing process [6] includes sequence of geometry coordinate inspection and flattening technological bases. These two sequences are repeated after each machining operations. Directions and the amount of displacement of reference plane in the machining process of aerodynamic parts can only be obtained by using the method of CMM (coordinate

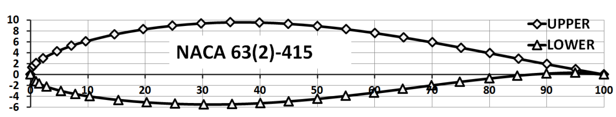

Fig. 2. NACA 63_2-415; airfoil definition points.

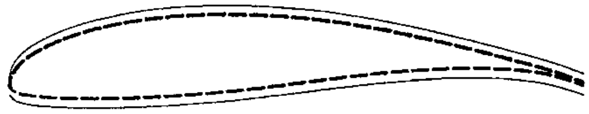

Fig. 3. Manufacturing error; translated airfoil.

measuring machine) coordinate metrology. This is why the technological process cannot be planned and prepared in advance completely [5].

Geometry inspection is the key of quality management of whole manufacturing process. It is most important results of the final geometric inspections of the models assembly and the total time of manufacturing. In optimization of coordinate inspection activities, it is necessary to execute comprehensively [5]. It is necessary to cover the preparations and execution time of metrological task.

During manufacturing process of freeform surfaces that form models of aircraft lifting surfaces, there may be a few characteristic errors [6]. Error analysis of the shape and position allows making corrections or changes to the technology chosen structure of the model and its lifting surfaces. The quality of the results is evaluated by analyzing the inspection accuracy of the measurement and evaluation of measurement errors.

Translated airfoils in the perpendicular direction to the plane of suspension are shown in Fig. 3. This error basically has several causes, but the most common is the wrong tool length compensation during initial setting by the CNC (Computer Numerical Control) operator.

The second important cause of airfoil translation is the thermal deformation of machine tools. Error occurs, if the upper side of airfoil is made in a thermal balance and the opposite side in the second. A typical situation occurs, when the processing is completed in one working day and machine has reached operating temperature. Machining opposite side begins with the second work day and cold machine leads to deviations although the machine operator to comply with all the activities required conversion.

Translated airfoils in the direction parallel to the plane of the suspension often appear. This error occurs in the incorrect setting of the machining coordinate system of the work piece. It manifests itself as an upper profile translated in relation to the lower profile. In these cases, the piece usually is rejected. Very rarely, only if it occurs in the earliest stages of manufacturing, can this error be improved. One of the basic parameters of the airfoil leading edge radius becomes undercut. The most common cause is insufficient experience of the operator on CNC milling machine.

Airfoils are equidistant from the theoretical shape; the same variation occurs in the upper and lower surfaces shown in Fig. 4. Error occurs in five-axis milling machine, when the cutter is constantly perpendicular to the surface to be processed. It occurs due to the mismatch

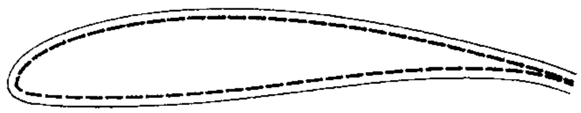

Fig. 4. Manufacturing error; equidistance airfoil.

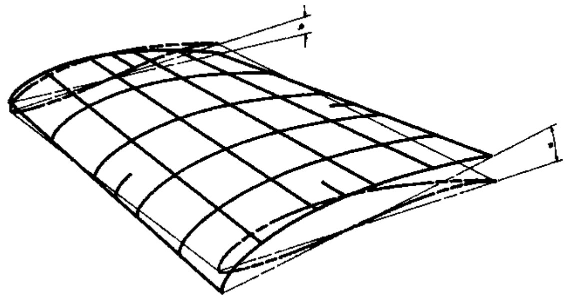

Fig. 5. Manufacturing error; twisted airfoils.

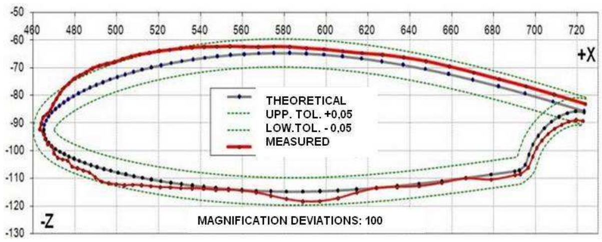

Fig. 6. LASTA-2 wind tunnel model (scaled 1:5), deviation of clean wing (no flaps); left wing, section 210 mm from central line (CL).

point of rotation defined by postprocessor (pivot point) and the same settings on the five-axis milling machine. These errors are easily corrected. It is necessary to repeat previous machining operation.

Another cause is the difference between nominal measures of cutter (ball-end) and used during generating the tool path. It occurs due to re-sharpening cylindrical cutter with ball end. This avoids the use of cutters with taper cut and spherical end. Sharpening of cutting tools leads to the shortening them, but nominal measures are not changes.

Twisted airfoils (profiles) in successive sections rotated in relation one to each other, as shown in Fig. 5. This error almost always occurs in manufacturing of lifting and control surfaces. Several elements influence the occurrence of these errors: chosen materials, chosen technology process, cutter with low wear resistance, and non-sharp cutter. The main cause is the residual stresses in the work piece after machining operations.

The waves of surfaces are the results of vibration and wear of cutting tool. Eliminating these errors requires using very sharpen carbide cutting tools. In reality (Fig. 6), the total error is a combination of all previously described manufacturing errors.

4.1. Angular relationships of aerodynamic surfaces

Position deviations of aerodynamic surfaces are just as important as the form deviation. For airplane defines the permitted deviations of wing dihedral angle and wing setting angle [8].

Angle is semi-space between two planes or two lines. The angle between two planes is the angle between the vectors of their normal. Apparently seems impossible to determine the angular relationship between two elements of free-form surfaces.

Transformation matrix exactly defines the position of the wings in absolute (airplane) coordinate system. Components of the normal vector of the WRP (Wing Reference Plane) give information about setting and dihedral angle, as shown in Fig. 6.

Table 1

WRP transformation matrix (airplane Lasta-2, wind tunnel model, scaled 1:5)

	X	***Y***	***Z***
	WRP OriginTranslation [mm]		
	565	0	−104
	WRP Axis Rotations		
I	0.999391	0.001826	0.034852
J	0.000000	0.998630	−0.052336
K	−0.034899	0.052304	0.998021

A typical example of a transformation matrix is shown in Table 1. The data in the table refer to the aircraft LASTA-2 wing which is designed by MTI Belgrade. Component "I" of the normal vector along the X axis gives the value of the wing setting angle (inverse cosine 0.999391 = 2°). Component "J" of the normal vector along the Y axis gives the value of the wing dihedral angle (inverse cosine 0.998630 = 3°). Figure 7 shows aircraft LASTA wing position in space.

Angular relationships of lift and control surfaces, wings and all the elements needed to determine the model for wind tunnel testing and are essential to the quality of the final assembly [8]. In relation to the measurement of airfoil shape deviation from this determination is complicated and requires complex mathematical models and calculation. It is necessary to find the plane that represents the wing and calculate the required angular relationships such as the wing setting angle and the dihedral angle.

The plane represents the position of the wings in space is Wing Reference Plane – WRP. This plane is not material and its direct measurement is impossible. Modeling of airplane wings in the CAD/CAM system begins by defining the WRP.

Originally developed measurement procedures WRP position a flow chart was presented in paper [7].

WRP measuring is based on well-known equations of analytical geometry, obtained by dividing the line segment in a given ratio. Coordinate of WRP points *w*, witch divide a line segment "***ul***" (u_{Ti} are points on upper airfoil side, l_{Ti} are points on lower side**)** in given ratio "$\boldsymbol{\lambda}$" are calculated according to vector equations (1).

$$w_{Ti} = \frac{u_{Ti} - \lambda_i \cdot l_{Ti}}{1-\lambda_i}; (i = 1 \cdots n) . \quad (1)$$

Dividing parameter $\boldsymbol{\lambda}$ is defined by eq. (2).

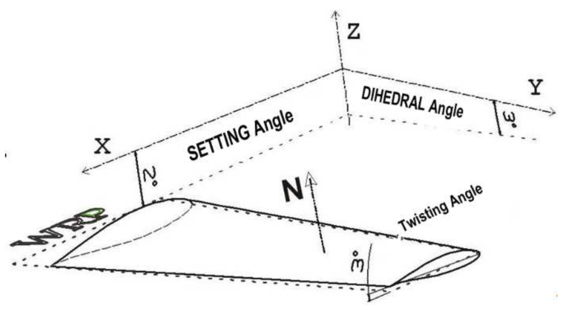

Fig. 7. Wing position in space (airplane LASTA).

$$\lambda_i = -\frac{|u_i w_i|}{|l_i w_i|} = -\frac{m_i}{n_i}; (i = 1 \ldots n) . \quad (2)$$

In specific case, $\boldsymbol{\lambda} = -1$, equations (1) give a coordinate of midpoints, equations (3). For symmetric and non-twisted airfoil dividing parameter is always $\boldsymbol{\lambda} = -1$. Calculation of WRP is simplified [18]; the theoretical and measured points also, are arithmetic midpoints, vector equation (3).

$$w_{Mi} = \frac{u_{Mi} + l_{Mi}}{2}; (i = 1 \cdots n) . \quad (3)$$

In accordance to paradigm of coordinate metrology, the measured coordinates of WRP can be obtained by applying vector equations (4).

$$w_{Mi} = \frac{u_{Mi} - \lambda_i \cdot l_{Mi}}{1-\lambda_i}; (i = 1 \cdots n) . \quad (4)$$

Equations (1) and (4) are applied to the same set of points ([18]. Equation (1) on the set of the theoretical coordinates obtained from CAD – index "*T*", and equation (4) on the set of the measured coordinates, obtained from CMM – index "*M"*.

The essence of this approach is the following: errors (form deviations) due to machining are small compared to the dimensions of the wing. If the paradigm of coordinate metrology applied to all geometric feature (prismatic, revolute, helical, cylindrical, planar and spherical) then it can be applied to free-form feature. This is the reason for applying the same set of equations for theoretical and for measured coordinates.

5. RELATED WORKS

Extensive studies [11] as well as the report [12], the verification of the accuracy of the airfoils geometry are done in only one section. Measuring a single cross-section is not enough to make sure that it is valid for the full wingspan. In several cases the deviations leading edge and trailing edge multiple times exceed the tolerance. The authors note [11]: "*the wind-tunnel data may not be an accurate representation of the true airfoil performance*".

Optical methods significantly reduce inspection time compared to CMM with contact probes.

Optical measurement system based on photogrammetry is presented in the paper [13]. Inspection system, simply called "WinGS" (Wing Geometry Sensor), consists of two CCIR video cameras and a fringe projector with a halogen lamp. System is a great help to the worker during the final polishing by sand paper.

Presented optical system in the paper [14] is very similar to the previous one. This optical system projects various fringe patterns onto the wind tunnel model surface. Deviations from CAD geometry are shown in gray-color gradients over the whole wind tunnel model.

Optical measurements wind tunnel models using laser scanning method are presented in the paper [15]. This inspection system use triangulation technique to determine the coordinate position of points on the wind tunnel models surfaces. The CMM, with a touch trigger probe, is used only for positioning reference points over the wind tunnel model surfaces. All scanned data are exported as an electronic 3D point cloud and compared with CAD file. Differences between actual and designed geometry are presented by colors on the wind tunnel model and scale on the computer screen. Measured geometry could be a good basis for advanced calculation. It is necessary to distinguish "form deviation" and "position deviation".

Comparative analysis of two optical systems by airfoil measuring in the laboratory condition, geodetic tachometer and photogrammetry, is presented in the paper [16]. Wing segment was measured as an object of unknown geometry. CAD files obtained by Reverse Engineering were compared. Authors presented the advantages and disadvantages of both systems: price, speed, environmental condition dependence, points cloud density and accuracy. This excellent analysis would have to be complted with a comparison with the native CAD.

Combination of optical and contact measurement method presented in the paper [17]. Combining overcome the disadvantages of both methods. The wing model defined with DU96-W-180 airfoil was measured in seven sections with the CMM. CMM measurements of the airfoil provide high accuracy in the chord direction and low accuracy in the cross direction. In the next step, the upper and lower surface of the wing was measured by optical method based on photogrammetry. The result is points-cloud with measured 3D coordinates of the wing model. These two sets of measured coordinates are combined using the Bayesian methods. The resulting 3D model represents the measured wing using two different techniques. The result is redesigned wing compared to the original CAD model.

Previously analyzed papers do not distinguish "form deviations" and "position deviations". To make the results of the measurements were correct these deviations should be separated [18]. For example, if wing semi-span is 1000 mm and allowed dihedral angle deviation is 0.1°, position deviation of wing tip is 1.745 mm. This value greatly exceeds the form tolerance of ± 0.05 mm. Possible they could be completely mistaken conclusions.

6. AIRFOIL MEASUREMENTS OPTIMIZATION

The time spent to coordinate inspection is a summation of all activities in the coordinate metrology laboratory. These are the times of thermal stabilization, setting part in the CMM working area, setting the coordinate system of inspections, probes calibration and execution of metrological task.

Results of geometric inspection of wind tunnel elements are essential for management of the manufacturing process. After each operation of contour milling of wind tunnel models elements, coordinate inspection is required. Results of the inspection indicate that the process is managed according to defined quality parameters.

For operations that are repetitive, as is the case with wind tunnel models coordinate inspection, is interest to minimize all measurement time. The interest is to minimize these times, so that the measurement accuracy and reliable of results be at a high level.

6.1. Measurements Accuracy

Measurement accuracy depends on the operator, environment conditions, work piece and CMM. It can be assumed that the influencing factors operator – environment – machine have a relative importance of approximately 100:10:1 in causing deviations [9].

Accuracy of coordinate measuring machines checked periodically, usually once a year, and is executed by an accredited laboratory according to the ISO10360.
Information on the impact operators are insufficiently available although probably the most influential of the differences in measurement results. In order to achieve reliable results it is necessary to focus on operator training. EUKOM [9] is a European coordinate metrology training program with three defined levels: User, Operator and Expert.

CMM operator has greatest influence on measurement errors during the adjusting inspection coordinate system [10]. For the purpose of solving the problem of orientation of the coordinate system to the wind tunnel models aerodynamic surfaces, at MTI developed a special method fully described in [5].

CMM programmer defines the number of control sections and the number of points for each section. The operator has no influence on this choice.

6.2. Developed method

The number and position wing control section of wind tunnel models is defined by design requirements and testing conditions. Their position is usually defined wind tunnel test engineers. Some sections are mandatory [18]: wing tip, sections with the holes for the measurement of pressure distribution, section close to fuselage. Theoretical wing root section is located in the plane of symmetry and cannot be measured. Additional control sections must allow the identification of whole changes of wing geometry.

The minimum number of points of airfoil coordinate inspections obtained from the condition that all deviation of applied interpolation curve to wing surface are within the defined tolerance [5]. For interpolation curve the most commonly used spline with cubic segments between the defining points. Increasing the number of coordinate inspections points will increase the total time of measurement, but will not increase the accuracy of measurement. Similarly, to the analytical curves, the minimum number is defined geometrically to the maximum is an infinite number. The optimal number of points obtained on the basis of class measurement accuracy and accuracy class of CMM.

Interpolation model will be applied over the set of measured airfoil points for the selected CMM. Selected criteria will be accuracy of CMM for measurements length (airfoil chord) increased by the value of the CMM measurement uncertainty. ISO 14253 provides that compliance zone expands to the value of the measured uncertainty. This is reason why CMM measurement error "*E*" (ISO 10360) as a criterion for deciding, increased by the value of the measurement uncertainty "*U*".

This criterion is provided that the error caused by the applied mathematical model will have a greater impact on the measurement error of the airfoil. Further increase in the number of control points will not increase the accuracy of measurement. The resulting number of measuring points is minimal for selecting criteria.

Thus specified minimum number of measured points is not limitation for increasing the number of inspections airfoils control points. Further increases in the number of interpolations points will be "covered" by CMM error. Increasing the number of control points will result in increasing the time for execution of metrological task. For operations coordinate inspections that repeat, the main interest is that the used time will be minimal.

6.3. Experimental results

Developed a method of minimizing the total number of airfoil coordinate inspections control points can be executed automatically on the CAD/CAM system. The open architecture of these systems and the appropriate auxiliary functions allow the practical implementation of the described method.

Testing of the developed method was performed on wind tunnel model of aircraft "Lasta-2", scaled 1:5. Complete wind tunnel model geometry is defined at the CAD/CAM system. The developed method was applied on the wing of the wind tunnel model as the most responsible part of the assembly. Wind tunnel model is shown Fig. 1.

For the measurement length L = 205 mm (chord length) of selected control section calculated the accuracy of CMM measurement according (ISO 10360) equation:

$$E = \pm 4 + 4 \cdot 10^{-6} \cdot L\,. \tag{5}$$

Calculation using equation (1) obtained from accredited laboratories give us CMM error E = 0.0048 mm and measurement uncertainty U = 0.0014 mm.

In a series of experiments, the number of airfoil measured points was increasing. These points were used for the polynomial interpolation. Polynomial interpolation was selected cubic spline, which is fitted using least squares (Gaussian best fit). For each of the fitting curves, CAD/CAM system checks the deviation from the designed wing surface. Curves deviation from surface was checked at 200 discrete points on a constant step along curve. These 200 discrete points is sufficient for an accurate assessment of deviations. Deviation results are presented in Tables 2 and 3, separately for upper and lower wing surfaces.

The first column in Tables 2 and 3 is the number of points used for interpolation. The second, third and fourth columns in Tables 2 and 3 are the maximum, average and minimum deviation polynomial interpolation from the wind tunnel model wing. Minimum deviations are zero, because some segments of the polynomial interpolation are located right on the surface of the wing.

The last column in Tables 2 and 3 present number of points (200 totals tested) which are outside the defined tolerance.

The maximum of curves deviation is shown graphically, Fig. 8, in dependence of the number of interpolation points.

Table 2

Deviation checking: left wing, upper surface, wind tunnel model "Lasta-2", section 210 mm from CL

	Upper surface; Deviation checking 200 checked points along curve			
No. of interpolation points	**Max.**	**Aver.**	**Min.**	**Out-Tol points**
18	0.0567	0.0030	0	34
26	0.0221	0.0014	0	17
33	0.0088	0.0010	0	9
41	0.0033	0.0003	0	0
80	0.0020	0.0002	0	0

Table 3

Deviation checking: left wing, lower surface, wind tunnel model "Lasta-2", section 210 mm from CL

	Lower surface; Deviation checking 200 checked points along curve			
No. of interpolation points	**Max.**	**Aver.**	**Min.**	**Out-Tol points**
18	0.0509	0.0030	0	36
26	0.0174	0.0014	0	18
33	0.0086	0.0009	0	9
41	0.0051	0.0004	0	0
80	0.0028	0.0001	0	0

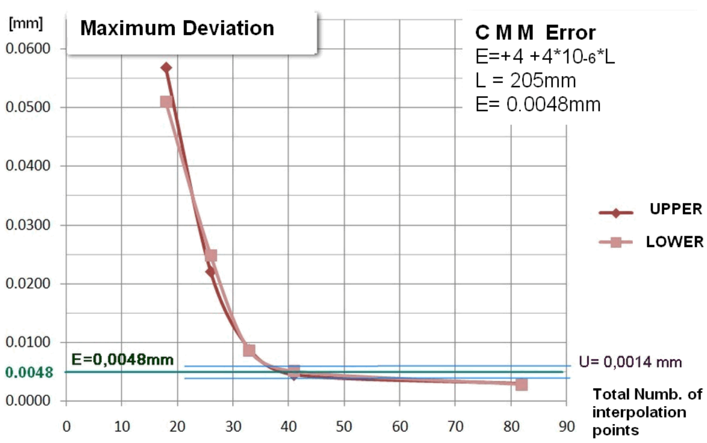

Fig. 8. Maximum deviation graph based on Tables 2 and 3.

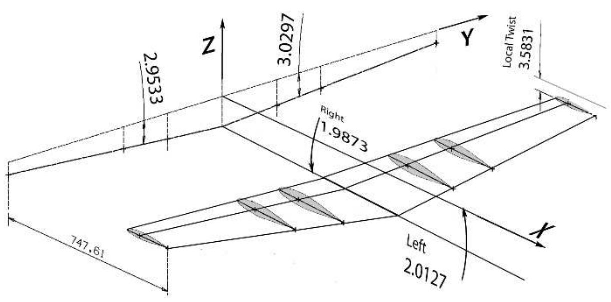

Fig. 9. Measured Dihedral and Wing Setting angle, wind tunnel model LASTA (model scale 1:5).

Figure 8 shows, for a selected wing cross section minimum number of measuring points for the upper and lower surfaces 41 (total 82). Thus specified minimum points number, ensure that the applied mathematical model of cubic spline interpolation for selected airfoil to be within the area of measuring machines precision ($E \pm U$).

Increasing number of the measurement points (100, 1000, 100000, 1000000) will not affect the accuracy of measurement. Execution time on the CMM will be drastically increased which results in an increase in direct and indirect costs [5].

Wind tunnel model of airplane LASTA, shown on Fig. 1, has measured setting angle 1.9873° for right wing and 2.0127° for left wing; theoretical value is 2°. Dihedral angle for left wing is 2.9533° and 3.0297° for right wing. These values are very close to theoretical value of 3° and within a defined tolerance. Measured value of local twisting of airfoil on wing-tip section is 3.5831°; theoretical value is 3.5°. Results are shown on Fig. 9.

7. CONCLUSIONS

Production quality control model of aircraft wings developed method provided the maximum material management [6]. Critical activities in the technological process of making the wing is moving reference plane of machining. These displacements, after each operation, provide a uniform distribution of additives for machining operations that follow. Results coordinate inspection control sections are analyzed according to established criteria and determine the values and directions of moving reference plane of machining. Established criteria in each phase of the airfoil to the measured deviations are within the scatter of the "six sigma". Such strict criteria decision making is set by the fact that the coordinate inspections performed a minimum number of points of the developed method. Methods presented in this section to minimize the time of preparation and execution of metrological task and ensure achievement of planned quality model aircraft.

The developed method is part of the wind tunnel models manufacturing management. Method of optimizing the number of airfoils control points with the method of WRP measurement [7] and the method of setting the coordinate system of inspection [5] are made together complete set. Developed and presented method was successfully applied on several international projects.

One of the examples of implementing is the wind tunnel model shown in Fig. 11. It is transport aircraft half

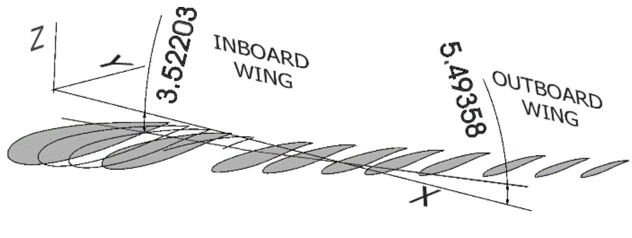

Fig. 10. Half model N2130: 12 measured wing sections and measured dihedral angle for inboard and outboard wing.

Fig. 11. Half model N2130; manufactured in MTI (Belgrade), wind tunnel testing in ONERA (Toulouse).

model with wing semi-span of 1893.5 mm. Model is manufactured in the MTI (Belgrade) and tested in ONERA (Toulouse).

This wind tunnel model has different dihedral angles for inboard (3.5°) and outboard (5.5°) wing. Inboard wing is measured in 4 sections and outboard wing in 8 sections. In the each of the cross-section measured between 40 and 60 points for upper and the same number for lower side of the wing, depending on the chord length. All measurement was executed at CMM with contact probe.

The measured points of the upper and lower surface of the wing were the basis for the application of the developed method. Obtained results are presented in Fig. 10.

The required time for wind tunnel models production is often several months. Developed method was guided by shorter and shorter deadlines of manufacturing wind tunnel models. Coordinate inspection is key-factor to managing manufacturing process of aircraft wind tunnel models to achieve planned and defined by contract quality. High demands of accuracy and the fact that it designs and produces only one assembly caused the development of the method described above.

The stated goals of optimization measurements airfoils are achieved.

REFERENCES

[1] E. Savio, L. De Chiffre, R. Schmitt, Metrology of freeform shaped parts. *Annals of the CIRP*, Vol. 56, No. 2, 2007, pp. 810–835.

[2] J.J. Muncey, D.M. Pote, *Design and construction of wind tunnel models − Report 20*, NATO Advisory Group for Aeronautical Research and Development (AGARD), 8th Meeting of the Wind Tunnel and Model Testing Panel, Rome – Italy, 1956.

[3] G. Ichikawa, K. Kasai, & S. Motogoe, *Estimation of the influence of profile error on aerodynamic performance for low-Reynolds-number airfoils*, Proceedings from ICAS 2008: 26th International Congress of the Aeronautical Sciences, Anchorage.

[4] D. Chen, Q. Wang, R. Hu, *Conditional sampling and experiment design for quantifying manufacturing error of transonic airfoil*. Proceedings from 49th AIAA (American Institute of Aeronautics and Astronautics) Sciences Meeting, Orlando, USA, 2011.

[5] S. Živković, *Coordinate metrology in manufacturing of the complex spatial forms with applications to the aerodynamic surfaces*, Military Technical Institute, Vol. LI, No.2, Belgrade, 2014.

[6] S. Živković, *Quality Management of Aeronautical Surfaces Manufacturing*, Management Studies, Vol. 4, No. 1−2, 2016, pp: 16−32.

[7] V. Majstorović, S. Živković, *Advanced method of wing reference plane measuring*, Proceedings XXI IMEKO World Congress, TC14, 2015, pp: 1496−1499.

[8] Z. Rendulić, *Mehanika leta* (Flight mechanics), Komanda RV i PVO, Belgrade, 1962.

[9] A. Weckenmann, S. Beetz, *EUKOM – European Training For Coordinate Metrology*, Conference Proceedings of the International IMS Forum - Global Challenges in Manufacturing, Valencia Spain, 2004.

[10] Tao-Hsien Hsu, Jiing-Yih Lai, Wen-Der Ueng, Jin-Zin Hwang, *An iterative coordinate setup algorithm for airfoil blades inspection*, The International Journal of Advanced Manufacturing Technology, No. 26, 2005, pp. 797–807.

[11] M.S. Selig, J.J. Guglielmo, A.P. Broeren, P. Giguere, *Summary of Low-Speed Airfoil Data*. Vol. 1. 1995, Vol. 2. 1996, Vol. 3. 1997, Spartech Publications, Virginia USA. C. Bak, P. Fuglsang, J. Johansen, A. Ioannis, *Wind Tunnel Tests of the NACA 63-415 and a Modified NACA 63-415 Airfoil*, Riso National Laboratory Roskilde, Riso-R-1193(EN), Denmark, 2008, on-line: www.risoe.dk/rispubl/vea/veapdf/ris-r-1193.pdf, accessed on: 28.07.2014.

[12] A. Zilker, D. Winter, *WinGS: Optical measurement and inspection system for aircraft wind tunnel models*, Proceedings from SPIE 3824: Optical Measurement Systems for Industrial Inspection, september 1999, pp. 334-337.

[13] G.M. Buck, *Rapid Model Fabrication and Testing for Aerospace Vehicles*, Proceedings from AIAA 2000: 38th AIAA Aerospace Sciences Meeting & Exhibit, Paper No: AIAA-2000-0826.

[14] G.M. Buck, M.A. Powers, M.S. Griffith, J.W. Hopkins, P.H. Veneris, K.A. Kuykendoll, *Fabrication of 0.0075-Scale Orbiter Phosphor Thermography Test Models for Shuttle RTF Aeroheating Studies*. Report No: NASA/TM-2006-214507, Langley Research Center, Hampton Virginia USA, 2006.

[15] D. Bručas, J. Sužiedelyt-Visockien, *Measuring surface geometry of airplane wing by means of two methods*, Journal Aviation, Vol. 13 No. 2, 2009, pp: 44−49.

[16] D. Boon, R. Dwight, J.J. Sterenborg, H. Bijl, *Uncertainties in a Wind-Tunnel Experiment using Bayesian Updating*, Proceedings from 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conferene. Paper No: AIAA-2012-1856, 2012.

[17] V. Majstorović, S. Živković, *Developed computer aided inspection method for free-form surfaces applied on aeronautical lift and control surfaces* – (ID 262), Proceedings IMEKO 11th International Symposium on Measurement and Quality Control, Cracow-Kielce, Poland, 2013, pp. 142–148.