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ERROR EVALUATION OF SECONDARY FREE FORM SURFACES IN COMPLEX PART MEASUREMENT

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Abstract: The main purpose of this work is to investigate the errors on secondary surfaces generated to joint free form surfaces of complex parts measured with Coordinate Measuring Machines (CMM) and modeled with CAD techniques. The approach involves the measurement of a complex part and fitting using NURBS curves and surfaces. The errors were determined by difference between determined points on secondary surfaces and fitted CAD surface.

Keywords: free form surface, error analysis, NURBS surfaces.

1. INTRODUCTION

Free form surfaces play an important role in part development nowadays associated to functional and aesthetic reasons. Its application is growing up as advances in manufacturing techniques can reduce errors and increase the part quality. Increased accuracy of inspection machines is demanded to evaluate part quality and Coordinate Measuring Machines (CMM) can successful perform this evaluation. Coordinate Measuring Arms (CMA) are a type of CMM that has flexibility and portability to measure large and small pieces in different locations like laboratory or field applications. The uncertainty of CMA is greater than that of conventional CMMs and they are used to perform tasks demanding portability like inspection of free form turbine runners.

There are some parts or devices that are designed and built having more than one free form surface. Examples are airplanes, submarines, helicopters and so on. By definition, a complex free form surface is composed of two or more free form surfaces. These complex surfaces are fitted using Computer Aided Design (CAD) modeling and particular strategy has to be used to get the final surface. At first step, it is required to separate the entire part in different sub-surfaces and carry out measurement of these individual surfaces. After measurement, CAD surfaces are fitted (primary surfaces) and secondary surfaces are developed to join these primary surfaces [1].

Different mathematical approach may be recommended nowadays to fit a group of points to a free form surface. In this way, the methodology of Non-uniform rational B-Splines (NURBS) are being increasingly used to perform this task. In this way, model adjustment error is reduced by smooth surface generated but it must be observed that error on generated secondary surfaces needs some careful attention [1].

This work intends to investigate the errors on secondary surfaces generated to joint free form surfaces of parts measured with CMA in CAD modeling. A small prototype of an airplane was used to conduct the investigation. The piece was measured with a six degree of freedom Romer CMA with accuracy 0.07 mm. Data acquired with Romer G-Pad software was exported in IGES format file and the principal and the secondary surfaces was reconstructed using NURBS lines and surfaces. Adjustment errors on primary and secondary surfaces were verified by difference between adjusted surface and measured points.

2. FREE FORM SURFACES MEASUREMENT AND CAD MODELLING

Free form surface measurement and adjustment is significantly different from measuring conventional and regular surfaces like circles and cylinders. The geometry is somewhat irregular and mathematical models are complex and varied. The measurement is carried out acquiring coordinates of points on surfaces and it is necessary to develop algorithms or use commercial software to adjust these models.

The measurement of free form surfaces is generally carried out using CMMs with contact or non-contact between stylus and surface. When using contact method, a mechanical stylus is connected to the CMM probe and the points are acquired in a sequence pre-established and planed through a measurement strategy. When using non-contact method, a CCD camera may be attached to the CMM and a large number of points are determined [1].

There are different ways of adjustment of a model to the surface and it depends on the method of data acquisition. When dealing with non-contact method, a point cloud is obtained and the adjustment is carried out by triangular mesh. When dealing with contact method, the points determined in defined sequences are adjusted to curves and surfaces. In both approaches, especially the second, the non-uniform rational B-splines (NURBS) adjustment method is growing up in application [1].

B-splines are considered as a parametric form of representation of curves and surfaces that uses control points, obtained with measured data, to fit data points to a number of third degree polynomials connected by points known as knots [1]. Figure 1 shows an example of a B-Spline curve with five control points (n) and three knots (k).

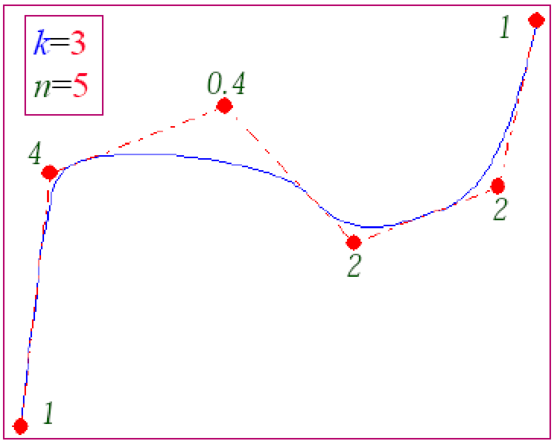

Fig. 1 – B-Spline curve showing control points [6]

A NURBS curve or surface is a special kind of B-spline fitted curve or surface in which weights are attributed to the control points, as these points "attract" more or less the fitted curve. The mathematical model of a NURBS surface is defined by equation 1. In this equation, $P_{i,j}$ are the control points, $N_{u,i}$ and $N_{v,j}$ are the normalized B-spline functions in directions u and v, $w_{i,j}$ are the weights of the control points [2, 3]. More details of these mathematical methods may be found in the literature [4].

$$S(u,v) = \frac{\sum_{i=1}^{n_u}\sum_{j=1}^{n_v} N_{ui}(u)\cdot N_{vj}(v)\cdot w_{ij}\cdot P_{ij}}{\sum_{i=1}^{n_u}\sum_{j=1}^{n_v} N_{ui}(u)\cdot N_{vj}(v)\cdot w_{ij}} \quad (1)$$

Measurement of complex parts having more than one free form surface is a complicated task as it is required to fit more than one free form surface. The inspection step to obtain data of each surface may be carried out according to segmentation of the part in individual simpler surfaces named primary surfaces. These primary surfaces are joined after fitting CAD model to each individual one and the surfaces constructed at the boundaries are the secondary surfaces. The accuracy of these secondary surfaces is closely related to the primary surface adjustment and its degree of accuracy is under investigation [3, 5].

3. EXPERIMENTAL STUDY AND RESULTS

The investigation of secondary surfaces errors was developed measuring a small airplane model, about 30 cm long, built in carbon fiber reinforced plastic. The model was clamped at one steel reference table at Metrology Laboratory at University of Brasilia and a Romer Coordinate Measuring Arm (CMA) was used to capture point coordinates on the airplane surfaces. The CMA arm reach was 2.5 m (diameter) in a spherical work space and the resolution of the CMA was 0.07 mm. Performance manufacturer test showed a CMA expanded uncertainty (95%) of 0.089 mm according to adapted ANSI/ASME B89 [7]. Figure 3 shows the experimental construction.

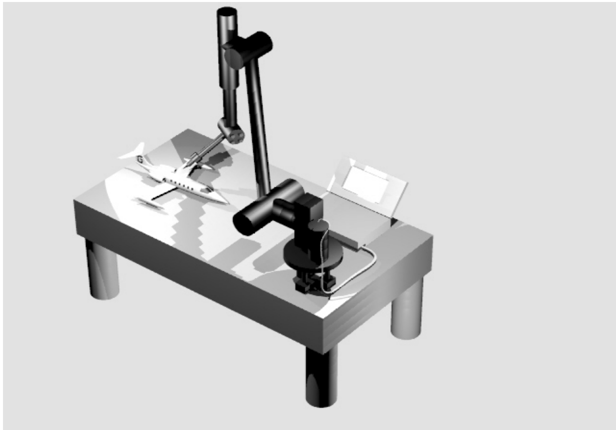

Fig. 2 – Experimental construction

The measurement was carried out according to a strategy of dividing the complete airplane in independent parts and then fit the primary surfaces. Thus, the fuselage, wings, tail and turbines were measured separated and NURBS models were developed to each one. The measurement of each primary surface was accomplished after tracing a grid pattern on the real surface and acquiring crossing grid points along predefined paths with the CMA. A NURBS curve was then fitted to each path and a NURBS surface was adjusted using these reference curves.

Figure 3 shows the NURBS curves fitted with measured data. It is here pointed out that measurement was carried out considering only half part of the airplane, e.g., turbines and wings were measured at one side and after than the others were fitted according to a central line passing by fuselage (straight line reference).

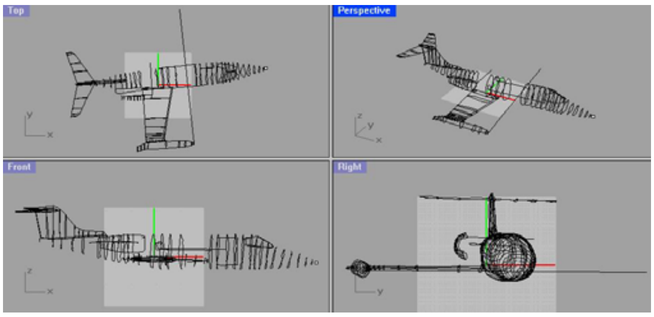

Fig. 3 – NURBS curves determined

Having built all primary surface models, the next step was to fit secondary surfaces to join all and built entire airplane CAD model. A condition to obtain a good agreement among the primary surfaces and the secondary surface is that the derivatives of the surfaces at boundaries must be equal. Commercial software dealing with NURBS has algorithms that perform this condition, referred usually as curve or surface continuity. Unless the secondary surface to be adjusted is a plane, it is important take some reference points at these joining positions during measurement to build secondary NURBS surfaces with good agreement in computers.

Detail of the secondary surface joining right wing and the right tank is shown in figures 4 and 5. These surfaces have NURBS models with local continuity and the aspect of the junction seems suitable. Anyway, quantitative evaluation must be carried out to determine numerically the deviations or errors of the CAD surfaces in relation to the physical part.

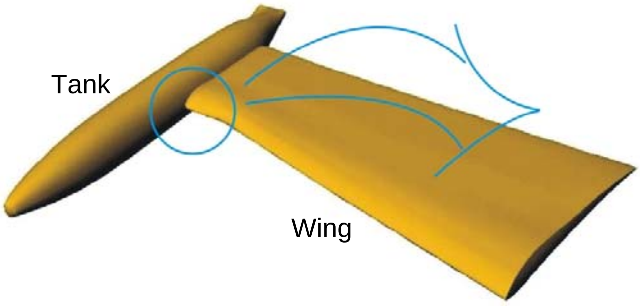

Fig. 4 – Secondary surface fitted connecting wing and tank

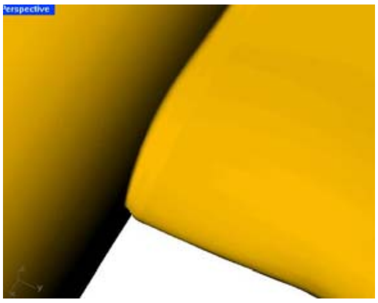

Fig. 5 – Detail of secondary surface generated at wing conection

The errors were determined by the difference between the NURBS fitted surface and the measured points on the surfaces. Figure 6 shows the adjustment error analysis of all airplane fitted surfaces. It was observed some particular regions where errors are bigger than the others (in red), as internal turbine contours, right tank extremities, vertical and horizontal stabilizer and upper surface of the left wing.

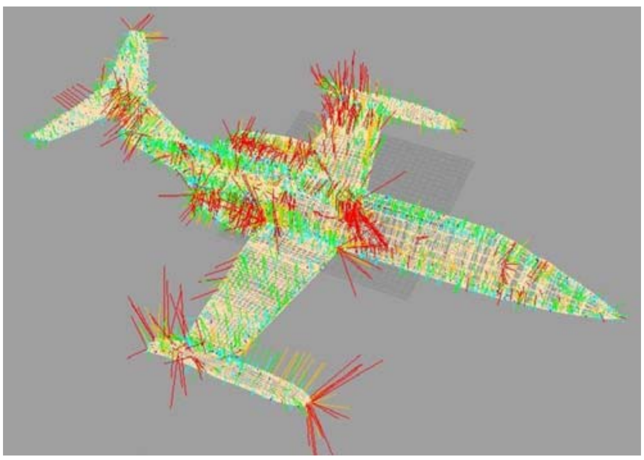

Fig. 6 – Airplane CAD model showing largest adjustment errors

These localized variations that were detected may be explained partially by error sources, observed during measurement step: occlusion in turbines, as accessing the internal turbine surfaces were difficult; lack of rigidity of the airplane fixation system, related to tank and wings extremities errors; fitting procedure used to build the second wing, by copying the first surfaces using a straight line as reference.

Table 1 shows the errors determined after analysis. Each error value was calculated determining the distance between the measured point and the nearest plane tangent to the surface. The results were computed by intervals and it was observed that a reduced fraction of points showed errors greater than 2 mm. The most pronounced errors were observed in turbines and the problem of occlusion of internal surface may be considered as the reason. The procedure to fit the second wing (left) and left side of airplane was the following in magnitude to influence the errors and it is recommended that the fitting procedure be considered with measurement of both sides of the airplane.

Tab. 1 – Analysis of errors between points and fitted surfaces

Surfaces	*Number of points and percentages (%) for each interval of error values* *Error intervals*					*Total number of points (%)*
	≤ 0.8 mm	**> 0.8 and ≤ 1.2**	**> 1.2 and ≤ 1.6**	**> 1.6 and ≤ 2.0**	**> 2.0 mm**	
Right wing + right tank	971 (80.9)	133 (11.1)	66 (5.5)	19 (1.6)	11 (0.9)	1200 (100%)
Left wing + left tank	515 (71.5)	91 (12.8)	65 (9.0)	32 (4.4)	17 (2.3)	720 (100%)
Right turbine	369 (65.9)	75 (13.4)	51 (9.1)	29 (5.2)	36 (6.4)	560 (100%)
Left turbine	236 (59.0)	66 (16.5)	53 (13.2)	25 (6.3)	20 (5.0)	400 (100%)
Vertical stabilizer	364 (77.5)	65 (13.8)	33 (7.0)	6 (1.3)	2 (0.4)	470 (100%)
Horizontal stabilizer	360 (85.9)	39 (9.2)	15 (3.5)	6 (1.4)	0 (0.0)	420 (100%)
Fuselage	2112 (84.5)	278 (11.1)	83 (3.3)	17 (0.7)	10 (0.4)	2500 (100%)

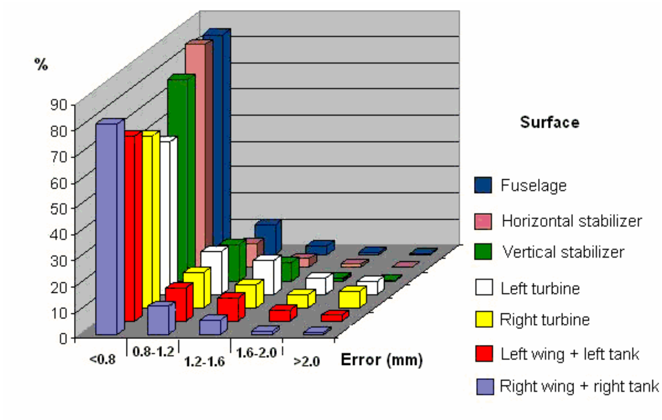

Fig. 7 – Histogram of groups of errors

It is important to point out that the great amount of errors (more than 59 %) were inferior to 0.8 mm, as shown in the second column of the table 1 and in figure 7. It was observed that turbines right and left presented the greatest errors and it can be associated to the partial occlusion of the surface. Figure 8 shows details of right wing and right tank of the airplane with an analysis of local errors.

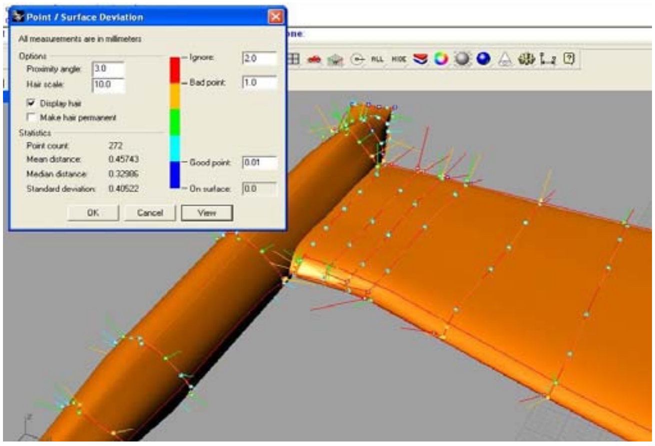

Fig. 8 – Fitting errors on right wing and right tank

The secondary surface developed to connect right tank and right wing is showed in figure 9. This surface was created using CAD software as a NURBS surface based on the boundaries of the wing and tank surfaces, these two developed one step before. A group of points was measured in this region and it helped to fit the secondary surface with an interactive procedure. It means that adjustment was carried out searching the best NURBS surface connecting the reference primary ones in a way to reduce the adjustment error.

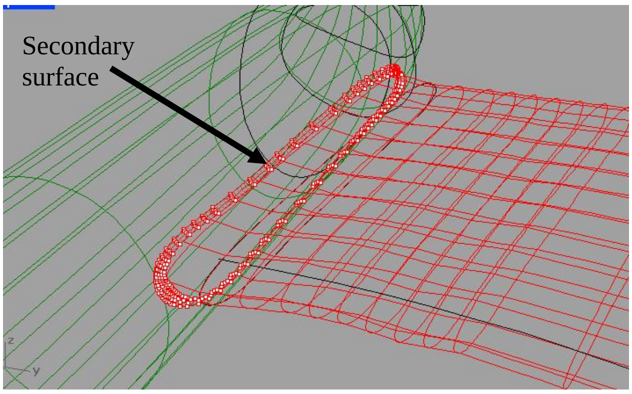

Fig. 9 – Secondary surface as a grid representation

Analysis of data obtained showed that the errors on secondary surfaces were close to the errors determined on primary surfaces (class < 0.8 mm), with almost all deviations (99 %) smaller than 0.8 mm for wing-tank connection surface. When dealing with turbine-fuselage surface connection, it was observed an increase in error values, as 85% of error of these secondary surfaces was lesser than 0.8 mm. This increase in error magnitude was related to primary adjustment errors observed in turbines, as occlusion was present when measuring in this place.

The dependence of secondary surface and the adjacent primary surfaces may lead to an incorrect or error prone adjusted secondary surface. This is a subject that is under more detailed investigation, as there is a limit when searching the best fitted primary surface. The knowledge of the uncertainty of primary surfaces when fitting NURBS to free form surface data would help to better quantify this relationship.

4. CONCLUSION

The procedure adopted to fit secondary surfaces in a complex free form surface part was suitable to fit the CAD model with good agreement. The analysis of the airplane example showed a large amount of errors, more than 59 %, was inferior to 0.8 mm on primary surfaces.

The relevant magnitude of some errors on these surfaces was associated to known error sources and a new measurement may be carried out to better adjustment, if required by incompatibility with part tolerances.

It was observed that the errors determined on secondary surfaces were of small magnitude and its values and frequency distribution depends on the errors of the primary surfaces. Special attention must be observed when having secondary surfaces connected to primary ones that have irregular general format or if error sources like occlusion is present.

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REFERENCES

[1] Y. Li and P. Gu, “Free-form surface inspection techniques state of the art review”, Computer-Aided Design, v. 36, pp 1395-1417, 2004.

[2] L. Piegl and W. Tiller, “The NURBS Book”, Berlin, Germany, Springer-Verlag, 1997, 646 p.

[3] Y. Zhongwei, Z. Yuping and J. Shouwei, “Methodology of NURBS surface fitting based on off-line software compensation for errors of a CMM”, Precision Engineering, v. 27, pp. 299-303, 2003.

[4] T. Várady, R.R. Martin and J. Cox, “Reverse engineering of geometric models – an introduction”, Computer-Aided Design, v. 29, no. 4, pp 255-268, 1997.

[5] Solomon, D. Curves and surfaces for Computer Graphics. Northridge, CA, USA, Springer Ed., 2006, 460 p.

[6] Iglesias, A., “B-splines and NURBS curves and surfaces”, http://personales.unican.es/iglesias

[7] ANSI/ASME B89.1.12M: Articulating Arm Coordinate Measuring Machine. New York: 1994.