CARES ON COMPLEX SURFACES GEOMETRIC MODELLING TO SIMULTANEOUS 5-AXES MILLING.

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Abstract. *This work brings an evaluation of the geometric continuity influence on the curves composition that will be guides and sections on the surfaces building over the suavity of the milling process on simultaneous 5-axes. On simultaneous 5-axes milling the tool guide is determined by the local normal vector on the guide-surface (which is normally milled) and, due to this fact, geometric discontinuities on the surface leads to the milling operation elapses on a non smooth manner, being subjected to jerks, marks on the piece and bringing the risk of a collision. The purpose of this work is to know if the worry about the geometric continuity on the curves composition which, later on, will compose the surfaces to be milled, has influence on the suavity of the milling process on simultaneous 5-axes. To do that, a complex surface is milled, got by the original data by specific program to turbines development. The surface and blade is composed by curves building by splines segments joint with continuities: geometric between* G^0 *and* G^2*, and parametric between* C^1 *and* C^2*. The best results were obtained using parametric continuity* C^2*.*

Keywords*: simultaneous 5-axes milling, CAD modeling, spline, geometric continuity.*

1. INTRODUCTION

The simultaneous 5-axes milling is an option to the manufacturing of complex geometries in cases where the tool accessibility is difficulted by adjacent geometry, which imposes the necessity to use tools with diverse orientations. However, this milling is characterized for present challenges of integrated knowledge of the process, since there are greater complexities on machine and computational aids systems operation.

A CAD model helps the designer with the graphic representation of the piece, as well as with the geometric information for other project and manufacturing activities as engineering analyses on CAE systems, volumetric calculus to be fulfilled during a study of injections molds, generation of tool trajectories for milling operations on CAM systems, etc. (Altmüller, S, 2001, Klocke, F.; Altmüller, S.; Markworth, L., 2001).

Nevertheless, in general manner, these activities are executed by distinct people of different sectors or even though by different firms or institutions. In this scenario, the geometric modeling step in a CAD system do not usually be enclosure by functional restrictions to the model someone else's to the own modeling process.

However, for the simultaneous 5-axes milling, there are greater constraints to the geometric model and to the surfaces mathematic representation. For this kind of milling operation, a CNC program out to have not only the tool positioning on work space (like on conventional CNC milling), but also orientation data of mill axis in relation to the piece. Thus, the manner of modeling the surfaces, the characteristics of their generator curves and the continuity characteristics with adjacent surfaces have high impact on the success and effectiveness of 5-axes milling operations (Balasubramaniam, M. *et al*, 2000).

This fact occurs because the tool trajectory generation methods available by commercial CAM systems determine the orientation of the tool axis in relation to the milled surface, mean based on the normal's local vector direction. This means to say that this orientation is function of the local surface curvature in the position of piece-tool contact and, as a consequence, its variation is inner connected to the surface suavity.

This relationship may be observed on the 5-axes milling practice when there are milled surfaces evidently irregulars, with sudden variations of curvature and directions and inflections points. In this kind of situation the tool-machine presents a dynamic behavior with suavity less, with the occurrence of locks and jerks which results in marks on the milled piece and increase on the milling time. There are also extreme situations that the geometric information inconsistencies contained on the virtual model leads the machine to an untimely behavior which can including cause collisions (APRO, 2008).

Among the geometric modeling factors that impacts the dynamic behavior of the machine in 5-axes milling operations, three of them are most important considered (Silva, A. S. A., 2006, Souza, G. O., 2010):

a) the surfaces suavity,
b) the geometric characteristics in surfaces transition regions,
c) the use of trimming operations of surfaces to their

The first two factors, related to the suavity and transition of surfaces, are connected with a propriety named continuity, and to understand your relationship with the generation of tool trajectories is necessary to know how they are generated on CAM systems and how the surfaces are represented in CAD systems. For this article, just the "surface suavity" factor is studied.

The suavity of parametric surfaces is directly connected to the suavity of the curves that compose them, and the suavity of these curves are assessed by a parameter called continuity. On graphics systems like CAD and CAM programs, complex curves usually are composed by diverse curves segments and the continuity of a complete curve is related to the form that both segments connected themselves. In respect to this subject Salomon says that:

> "There are two types of curve continuities: geometric and parametric. If two consecutive segments meet at a point, the total curve is said to have G^0 geometric continuity [Figure 1] [...]. If, in addition, the directions of the tangent vectors of the two segments are the same at the point, the curve has G^1 geometric continuity at the point. The two segments connect smoothly [Figure 1] [...]. In general, a curve has geometric continuity G^n at a join point if every pair of the first n derivatives of the two segments have the same direction at the point. If the same derivatives also have identical magnitudes at the point, then the curve is said to have C^n parametric continuity at the point" (Salomon, 2006).

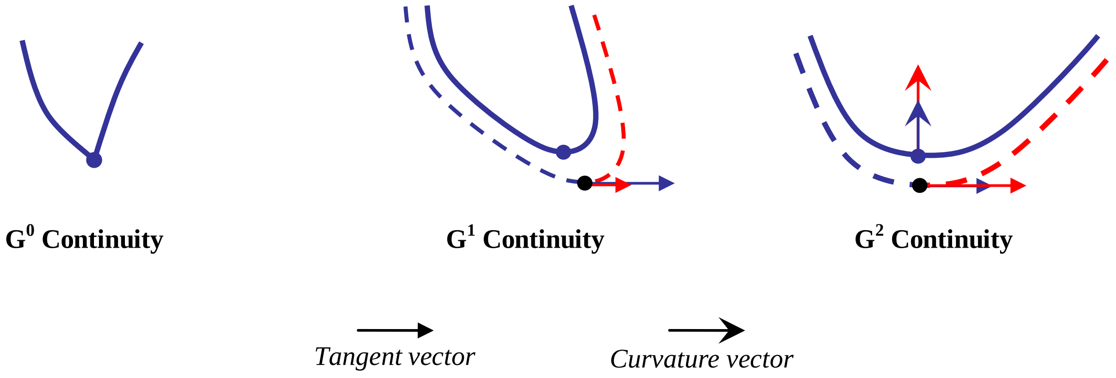
G^0 Continuity **G^1 Continuity** **G^2 Continuity**

Figure 1. Geometric continuities on curve segments (Adopted from Salomon, 2006, pp. 17)

Salomon continues in the next paragraph dealing with parametric continuity:

> "We can refer to C^0, C^1, and C^2 as point, tangent, and curvature continuities, respectively. Figure 2 illustrates the geometric meanings of the three types. In part C^0 of the figure, the curve is continuous at the interior point, but its tangent is not. The curve changes its direction abruptly at the point; it has a kink. In part C^1, both the curve and its tangent are continuous at the interior point, but the curve changes its shape at the point from a straight line (zero curvature) to a curved line (nonzero curvature). Thus, the curvature is discontinuous at the point. In part C^2 the curve starts curving before it reaches the interior point, in order to preserve its curvature at the point. Generally, high continuity results in a smoother curve.
> C^k continuity is more restrictive than G^k, so a curve that has C^k continuity at a join point also has G^k continuity at the point [...]". (Salomon, 2006).

The Figure 2, shows curves with C^0, C^1 e C^2 parametric continuity


C^0 Continuity **C^1 Continuity** **C^2 Continuity**

Figure 2. Curves with C^0, C^1 and C^2 geometric continuity between their segments. (Adopted from Salomon, 2006, pp. 17).

High-end CAD systems allow the modeling of splines with continuity degree between G^0 and G^2 and between C^0 and C^2. In other words, it is possible to determine that two adjacent curves segments have, further on coincident directions of tangents, the same curvature in the proximity of encounter point (Passador, F. E., 2010).

The surfaces suavity of a geometric model is basic to the suavity of the movements executed by the axes in a machine during the surfaces milling. It is because the 5-axes milling of complex surfaces is realized with CNC programs which contain tool trajectories calculated from these geometric models and, for such, the parametric curves are used (Souza, G. O., 2010).

This article has the objective to analyze the influence of the “surfaces suavity” factor on the simultaneous 5-axes milling, by means of the several possibilities of modeling from a same complex surface based on the geometric characteristics of theirs generator curves.

2. PROCEDURES AND EXPERIMENTAL APPARATUS

From a collection of calculated points and exported by a specific CAE system for the gas turbine design, 9 replicas of a model-surface were modeled by 9 distinct forms.

The distinction of each of the 9 surfaces occurred at the moment of built of the curves from the points. Three options of composition were defined:

- S-G0 – curve composed by a succession of 3 degree splines connected with G^0 degree continuity;
- S-G1 – curve composed by a succession of 3 degree splines connected with G^1 degree continuity;
- S-G2 – curve composed by a single 3 degree spline and with the whole knots with G^2 degree continuity;

Cubic (3 degree) polynomials were chosen, since they allow better descriptions of curves due to the continuity from their segments, as well as to be the least degree that allows the representation of traditional curves (Foley, 1996).

Each surface was modeled from 7 curves, being 5 as sections and 2 as guidance, and these three types of curves were used both to compose the section groups and to compose the guidance groups, which combined makes 9 replicas. Table 1 presents the composition of the 9 surfaces and the abbreviations that will be used to make reference to them from now on.

Table 1. Nomenclature and composition of the model-surfaces.

			guides		
			0	**1**	**2**
			S-G0	**S-G1**	**S-C2**
sections	**0**	**S-G0**	SUP-00	SUP-10	SUP-20
	1	**S-G1**	SUP-01	SUP-11	SUP-21
	2	**S-C2**	SUP-02	SUP-12	SUP-22

The surfaces were distributed in two rows and milled in a block of 105x278x50 mm 7075 aeronautic aluminum alloy, illustrated on Figure 3. The **u** and **v** directions from the parametric field are also indicated on this figure, which are coincident with the guidance directions and sections respectively.

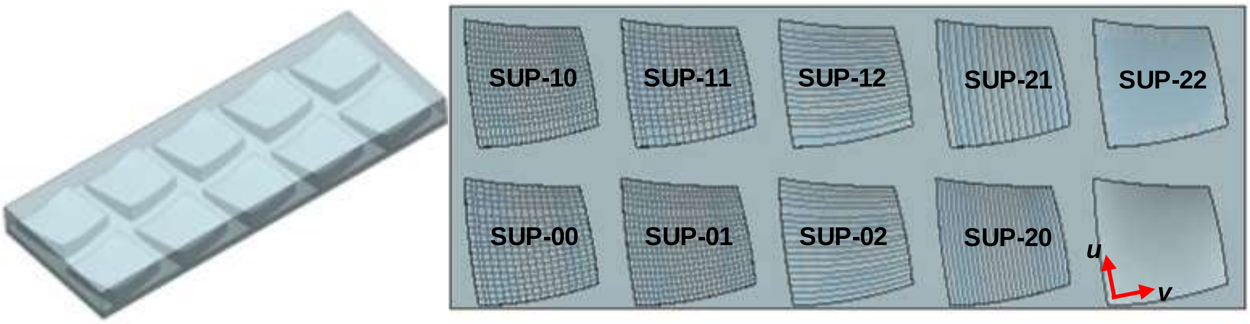

Figure 3. Surfaces distribution on milled block during the experiments.

The machine tool used was a Hermle C 660U 5-axes machining centre, equipped with a Siemens Sinumerik 840D CNC, and with translation movements applied to the spindle head and the rotation ones, A and C axes in this case, executed by the rotary table.

Before the finishing operation, object of the experiment, the surfaces were roughed and pre-finished in order to have a constant layer of 0,3 mm thickness stock. The final operation of all surfaces was done with the same two teeth 6 mm solid carbide ball-end mill.

The CAD/CAM system used for the geometrical modeling and to generate and pos-process the tool paths was the Siemens NX6. For the generation of simultaneous 5-axes milled tool path used on the test, there was applied the “variable contour” strategy from the strategy group for multi-axes milled. The method used by this strategy is the sloping tool, being the advance direction coincident with the **u** parametric direction (Figure 3), and the tilt and lead angles of 0° and 10°, respectively.

The linear method was chosen for the trajectory interpolation with ± 0,001 mm tolerance. The operation consisted of 200 zigzag passes, which implicated on a approximately 0,2 mm a_e, realized with 15000 rpm, 0,1 mm of f_z, 0,3 mm of a_p (Figure 4).

The NC programs of these operations were generated in ISO language, with interpolation linear command blocks (G1) with definition of final position for the linear and rotary axes (example of command block extracted from a program: G1 X47.428 Y174.711 Z-5.097 A=-19.718 C=DC(71.977)). There were also used the G642, SOFT and TRAORI commands, specifics from CNC Sinumerik 840D, to round the corners between the trajectories segments, jerk limitations and dynamic position of reference in rotary table (for more information about this function see APRO, 2008), respectively.

In order to allow analyses and comparison between the milled processes for the different surfaces, the real data acquisition of machine axes position and speed were made during the operation executions. For such function a data acquisition routine built on software Labview was used. This routine collected the data through a model network adaptor Siemens SIMATIC NET CP 5611 module, which allows a direct communication between the computer and the CLP’s of the machine tool. The microcomputer to which the plate is coupled has a 1,7 GHz processor, and 256 MB RAM memory.

Other two parameters used to compare were the surface visual inspection and the duration time of operations, which was calculated through the data provided by the acquisition routine that marked, in milliseconds, the recorder instant of each data collection.

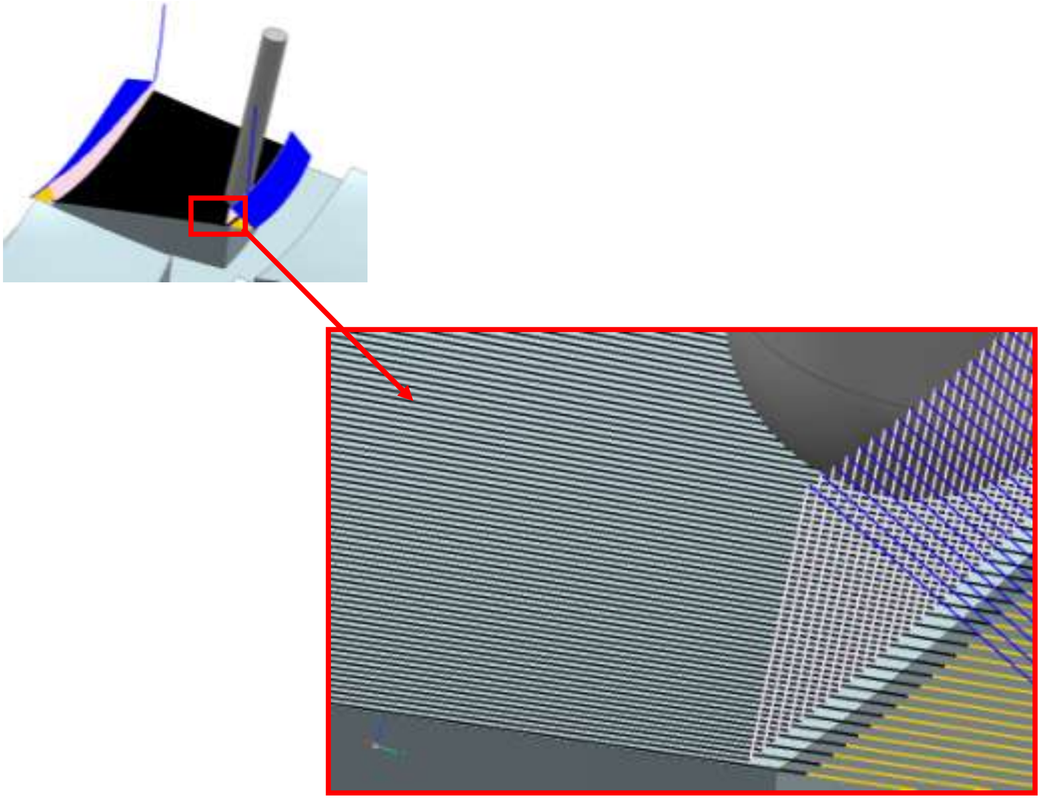

Figure 4. Trajectory illustration of the tool generated for the milled test. Above, a panoramic view, and below a detail of the first zigzag passes.

3. RESULTS AND DISCUSSIONS

The realized tests showed that the curves modeling forms that will compose surfaces to be milled by milling in simultaneous 5-axes interfere in the milling process. A view of Figure 5, which shows the piece with the 9 replicas of milled model-surface, is enough to show that there are differences on the superficial finish between the three surfaces with S-C2 (SUP-20, SUP-21 and SUP-22) guidance and the rest.

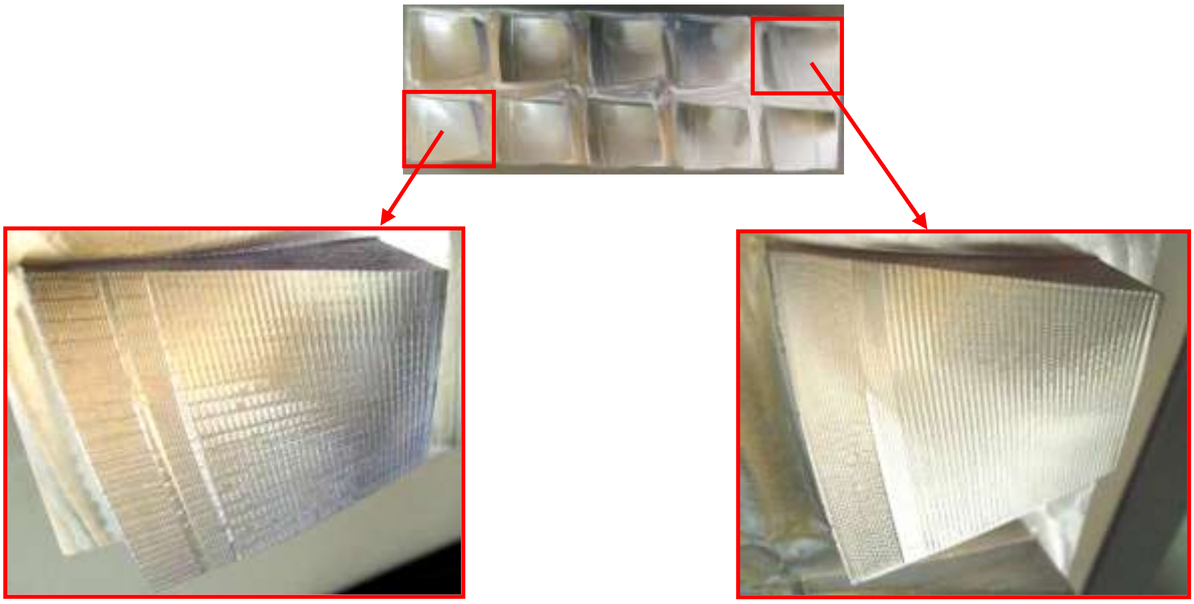

Figure 5. Aluminum Block after milling of the 9 model-surface replicas. In detail the surfaces, at left the SUP-00 and at right the SUP-22.

The simple observation of the machine behavior during the tests execution already shows signs from this difference. The SUP-20, SUP-21 e SUP-22 surfaces milling elapsed on a smoother manner and with advance movement continuous throughout the passes. This observation leads to the conclusion that the firs important impact decurrently from wrong modeling surface forms results on the sliding behavior of the machine.

The confirmation of this observation may be obtained from the evolution graphs of advance and linear axes speed trough Figure 6, which comprises the route section of axes movement corresponding to two tool passes.

It can be seen in this figure that the S-G2 (SUP-20, SUP-21 e SUP-22) surfaces with guidance are distinguished from the remainders. At the contrary that happens for the others, the advance speed curves (v_f) and the linear axes speed show a smoother evolution.

The non smooth behavior of milling speed evolution of SUP-00, SUP-01, SUP-02, SUP-10, SUP-11, SUP-12 surfaces is demonstrated graphically by the serrated aspect that the curves present, with their speeds varying from zero to greater values than 500 mm/min with a frequency more than ten times greater than the tool passes. This accelerations and decelerations lead to a garbled milling observed, with movements frequently interrupted.

Finally, it is important to observe that the negatives consequences from this sliding behavior are not confined to the finish superficial deterioration, since the milling time also differs in a meaningful way.

The frequently interruptions of the advance movement leads to a twice greater time to the milling of SUP-00, SUP-01, SUP-02, SUP-10, SUP-11, SUP-12 surfaces comparing with the SUP-20, SUP-21 e SUP-22 ones (Table 2).

Table 2. Milling time of model-surface replicas.

			guides		
			0	**1**	**2**
			S-G0	**S-G1**	**S-C2**
sections	**0**	**S-G0**	SUP-00 26,956 min	SUP-10 25,207 min	SUP-20 12,247 min
	1	**S-G1**	SUP-01 25,296 min	SUP-11 27,282 min	SUP-21 12,221min
	2	**S-C2**	SUP-02 24,763 min	SUP-12 24,937 min	SUP-22 12,388 min

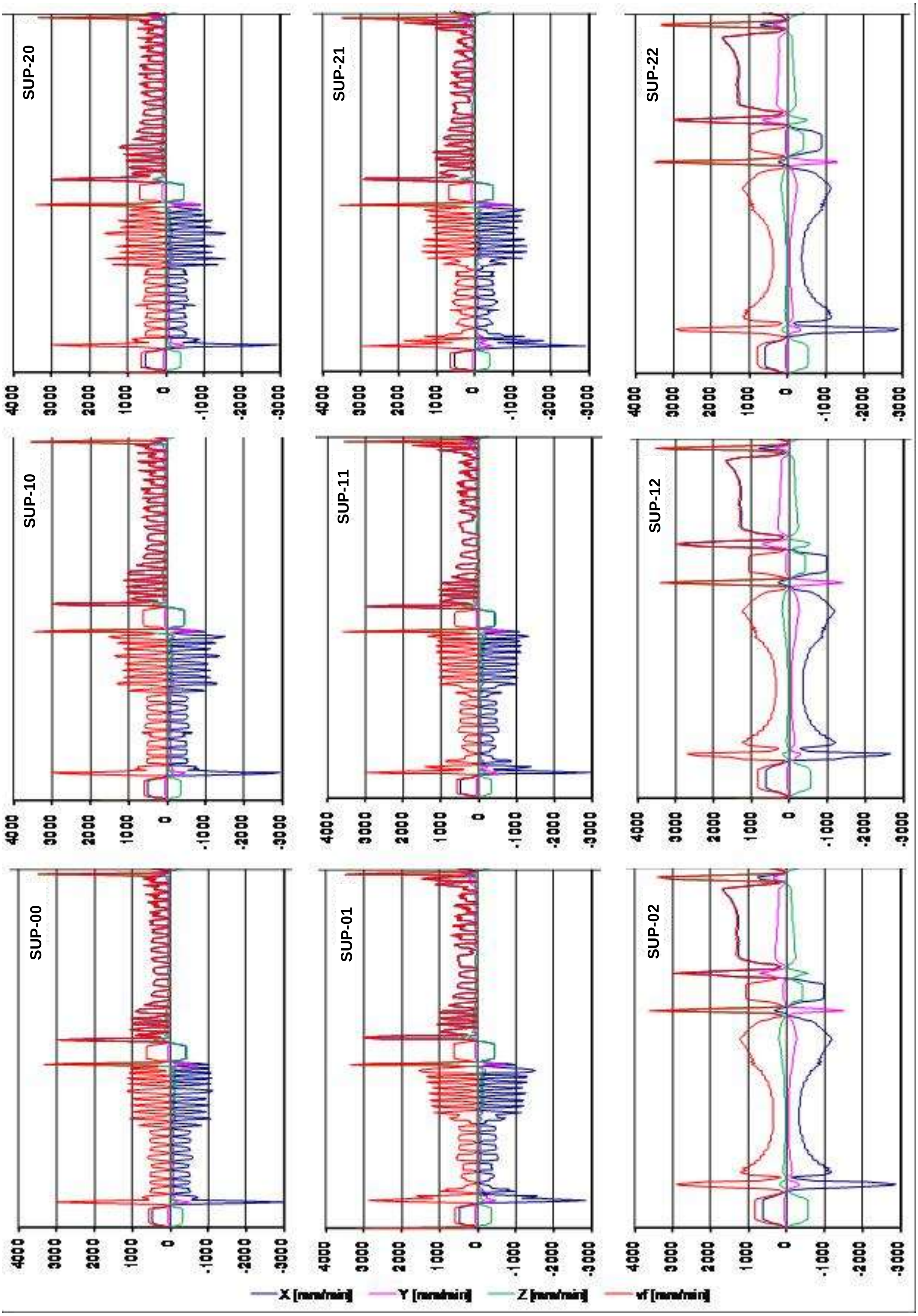

Figure 6. Real advance and linear axes speed throughout two tool passes

4. CONCLUSIONS

The study presented on this article shows that the practices adopted by the designers on the geometric model step of complex pieces and parts exert influence on the simultaneous 5-axes milling manufacturing. In one of the initial phases of geometric modeling, the curves building that will later on compose the surfaces, it must be care by the designer. How the experimental results showed, for the suitable simultaneous 5-axes milling, with smooth and continuous movements, is fundamental that the curves that compose the milled surfaces have C^2 continuity degree between their segments. Not even the fact that a spline be composed by polynomial curves that encounter each other at a tangent geometric continuity (G^1) guarantee the smooth milling. The last important conclusion is that, the operations suavity been affected, the productivity is also prejudiced, as the results herein presented show where the milling operations of six modeled surfaces with guidance-curves without geometric continuity C^2 had a duration more than 100% greater than the surfaces where this characteristic was respected.

5. ACKNOWLEDGEMENTS

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