# Programming of a Machining Procedure for Adaptive Spiral Cutting Trajectories

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*Abstract:* - The objective of this paper is to present a new adaptive spiral cutting method and its implementation in CAD/CAM software applications. A Visual Basic (VB) macro automatically generates a spiral tool path for the machining of pockets in aircraft wing components. The second part of the paper is aimed at improving the cutting methods for machining pockets with inclined walls. During the roughing operation, the proposed tool path takes into consideration the slant of the walls but also allows maximizing the quantity of material to be removed.

*Keywords*: CAD/CAM, cutting trajectories, adaptive spiral, high speed machining.

## 1. Introduction

Recent progress in high speed machining (HSM) have lead to significant gains in terms of machining time [1]. However, CAD/CAM software applications were not developed with this type of machine in mind. As a result, the cutting strategies that are offered within machining programs are poorly adapted to the HSM [2]. This is why numerous efforts are presently made by researchers to develop new cutting methods which are better adapted to the performances now available with actual machines [3].

One of the increasingly popular methods consists in generating a smoother tool path [4], without any sudden change in the direction of the tool [5]. This approach has an important advantage, particularly during the machining of pockets [6] largely found on aircraft wing components (Figure 1).

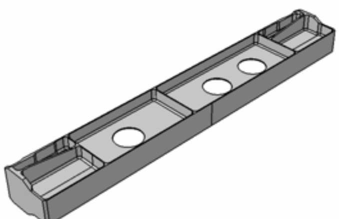

Fig. 1: Aircraft wing component with pockets

A smoother tool path presents the advantage of making speed more constant [7] and offers the possibility to machine the component at the highest available speed, when reachable. As a result, these time savings allow to increase the production rate [8]. However, actual design and machining software applications do not offer the possibility to fully take benefit of the machine capability.

This article aims to capitalize on this new approach to develop a machining procedure which involves an adaptive spiral tool path. This technique is based upon commonly used programming methods in CAD/CAM software applications [9]. The subprogram, which is written in Visual Basic, allows to automatically generate a spiral cutting trajectory.

The programming method used to generate a spiral adaptive tool path is based upon the following approach:

1) Perform a profile boundary offset;
2) Generate the cutting trajectory at the centre of the pocket (central spiral);
3) Generate the remaining cutting trajectory and adapt it to the pocket boundary;
4) Compute the radial depth of cut and the feedrate.

## 2. Boundary offset

The first step in the programming process consists in performing an offset of the pocket profile. This offset constitutes the tool path's final machining step. The calculations to offset the geometry are taking into account the tool's diameter and the stock allowance whenever there is a finishing operation.

The unit vector used for the offset of the pocket profile is calculated using the cross product between the tangent vector related to each element of the profile geometry and the tool axis.

In the case of a line which is offset towards the inside of the pocket (line P1-P2), as illustrated in Figure 2, the cross product of the P1-P2 vector (vector $a_1$) and the tool axis (vector b) generates the normal vector and thereby offset the geometry so as to create the P1'-P2' line.

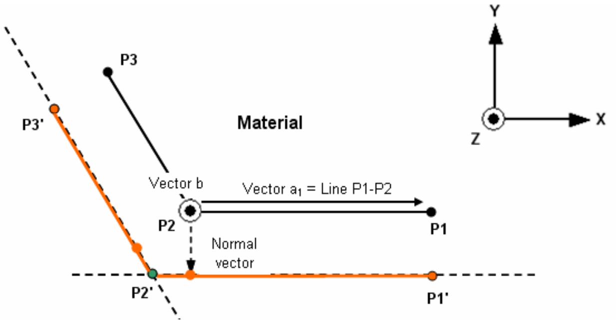


Fig. 2: offset of two (2) lines and computation of the new intersection point

The program proceeds in a similar way for the following line and computes the new intersection point (P2') between both lines.

In the case of a geometry comprising an arc of a circle, the main vector is depicted by the radius of the arc. As a result, this element boundary points are offset in the same direction as the radius. Some measurements need to be taken into consideration during the geometry offset. Depending on the radius of curvature in the pocket's corners, if the offset is smaller than the corner radii, there will be no overlap and therefore no element loss in the last stage of the tool path. In other words, if the tool's radius is smaller than the corner radii, there will always be a curve trajectory in the corners. Figure 3 illustrates the situation where the tool radius is smaller than the corner radius. No element loss is incurred and a circular trajectory (Arc P2'-P3') always exists.

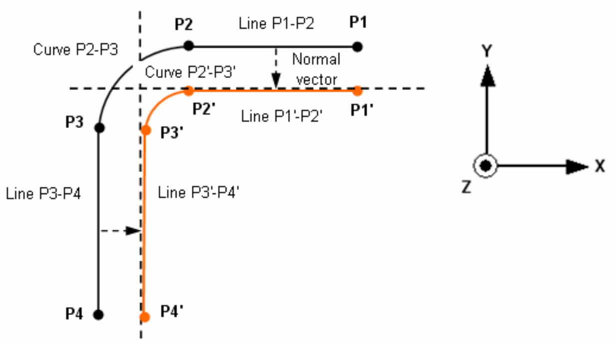


Fig. 3: Offset with no element loss incurred

The opposite situation may also occur. When the tool's radius added to the stock allowance is greater than the corner radius, the circle's arc is eliminated. An intersection calculation between 2 lines needs to be computed (see Figure 4).

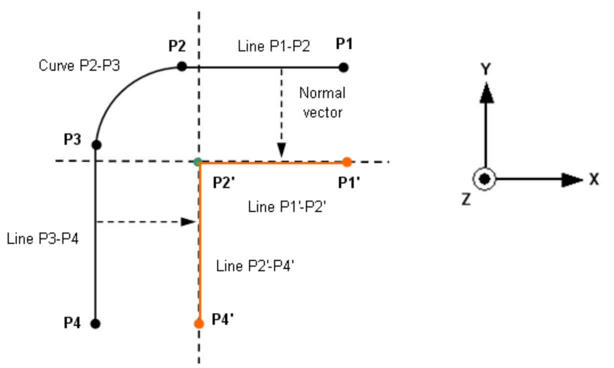


Fig. 4: Elimination of a circle arc and intersection between 2 lines.

Since the offset of line P1'-P2' and line P2'-P4', a new intersection point P2' had to be computed, to determine the tool path and allow the elimination of the interference arc P2-P3 (gouging). When the offset is too important, the main vector is greater or equal to the corner vector and the arc cannot be generated. As a result, this element is eliminated.

Depending on the pocket's geometry and the offset value, the program computes and redefines the geometric elements that are used to generate the final tool path which defines the boundary. In order to confirm that the programming allow an accurate geometry offset computation, several pocket profiles of various shapes were subjected to two (2) kinds of offsetting tests: an offset smaller than the corner radius and an offset greater than the corner radius. This simulation allows to determine when to eliminate certain geometric elements so as to generate the final machining step required on the pocket boundary.

As previously mentioned, depending on the corner radius and the offset value, the final trajectory can require an additional calculation to redefine the last machining stage. This stage is defined by a large number of points. A polynomial curve allowing the creation of the final machining trajectory will go through these points which are constructed as control points.

## 3. Automatic generation of the spiral toolpath

The second step of the procedure is aimed at creating the spiral tool path at the centre of the pocket. In order to do this, the program determines the coordinates of the pocket geometric centre and performs the required translation and rotation to make it coincident with the workpiece reference frame origin.

Once the geometry is located at the reference frame origin, the central spiral is generated according to the tool's diameter and the specified radial cut. This central spiral, which represents the beginning of the trajectory, is characterized according to the "C" parameter [10]. This parameter determines the ratio of the central spiral to the pocket's width. This parameter is also the geometric point where the spiral will start its transition so as to adapt to the pocket geometry. The "C" parameter is a proportion applied to the pocket width "*l*". As illustrated in Figure 5, a C=70% and C=30% circle determines the beginning of the transition of the spiral with the outer boundary.

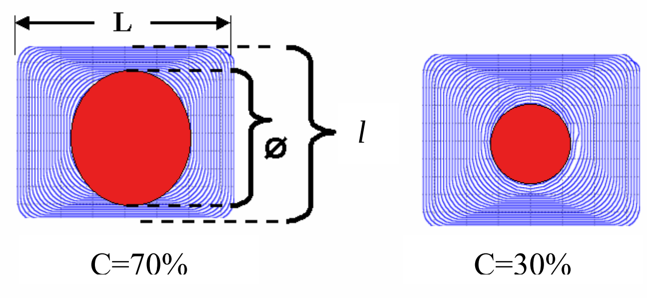


Fig. 5: Parameters for the generation of the spiral trajectory [10]

Based upon experimental results [10], the program uses a default spiral transition set at C=50%. The results obtained experimentally show that this parameter is optimal.

Therefore, the VB programming prototype generates a circular machining path at the start if the pocket has a square shape. If the pocket geometry has a rectangular shape, the initial path looks like a rectangular shape with circle arcs at its ends (Figure 6).

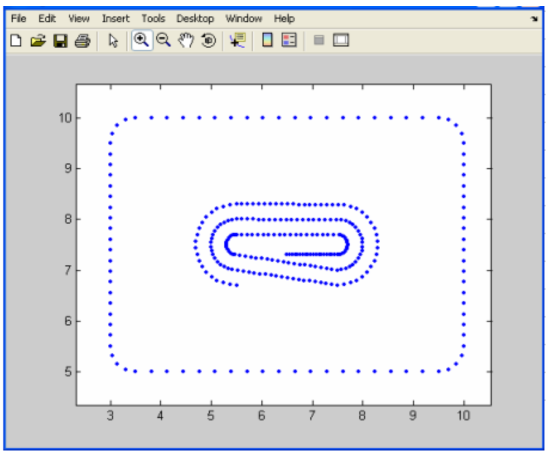


Fig. 6: Cutting trajectory at the centre of the pocket

After the generation of the central spiral, the remainder of the trajectory is generated by means of an inspection method which consists in performing a 360° scan of the geometry boundary. Considering that the pocket centre was initially translated at the coordinate system's (0,0) position, a fictitious line going from the point (0,0) and linking the last stage of the central spiral to the final stage, is used to distribute the control points. As a result, it is possible to complete the tool path for all the points which delineate the boundary. Figure 7 illustrates this process.

Once all the points are created, the program removes some of those located in the corners (see Figure 8). In this figure, which shows a rectangular-shaped pocket, one can notice the removal of some of the control points located in the corners. The interpolation curves replacing those points are splines. This technique allows the smoothening of the trajectory when the final polynomial curve used to delineate the tool path is generated. This is particularly beneficial to reduce sharp direction changes in the corners.

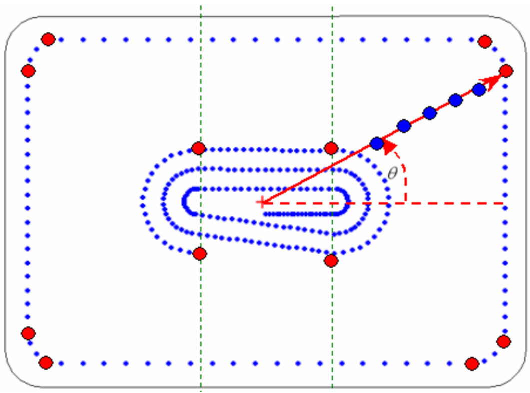


Fig. 7: Boundary inspection and distribution of the control points

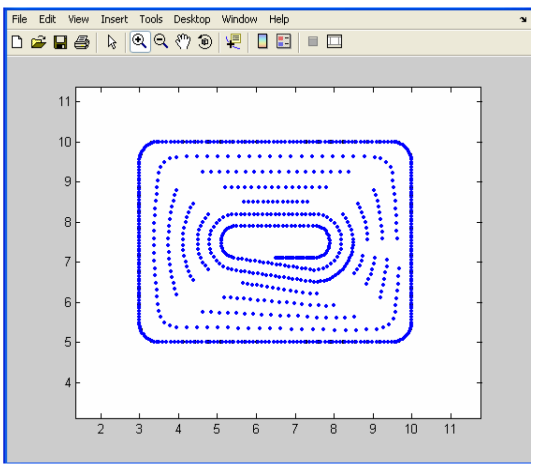


Fig. 8: Removal of the control points in the corners

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## 4. Calculation of the radial depth of cut and feedrate

Once the trajectory has been generated, the program computes the radial depth of cut. Because the tool path is kind of an adaptive spiral, the cutting thickness cannot always be constant. The method used to determine the thickness consists in measuring the distance between a control point and another control point located in the same place in the trajectory's following stage. The cutting thickness was calculated by using the least squares approach.

Most machining programs suggest slowing down the feedrate in the pocket's corners. Since the tool is almost entirely immersed in the material, a reduced speed contributes to an easier chip removal and more stable machining. As a result, the VB procedure can also take into account changes in terms of speed during machining, since the cutting thickness may vary.

Once the thickness is calculated for the whole trajectory, the program determines the feed correction. By specifying the feed and the "slowdown" value, a linear equation allows to compute the lead correction that is required. For the specified cutting thickness, the feed is entirely applied, whereas for the maximum cutting thickness, the reduced value of the lead is used at this point on the trajectory. The lead is therefore computed in a linear manner for the radial depths of cut lying between the specified thickness and the maximum thickness.

Figure 9 shows how the feed is corrected according to the cutting thickness, for a rectangular-shaped pocket with a feed specified at 600 in/min and a 75% slowdown. The feed is specified with respect to the location (control points) on the tool path (figure 10).

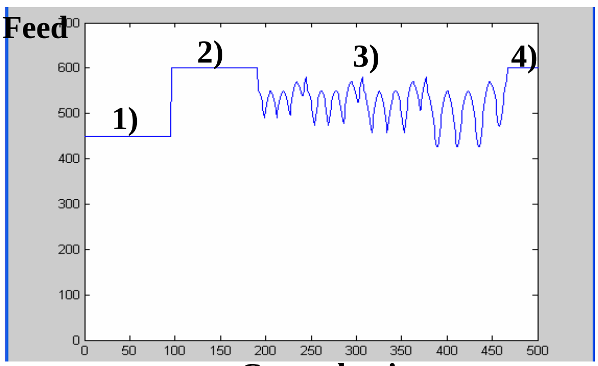


Fig. 9: feed variation

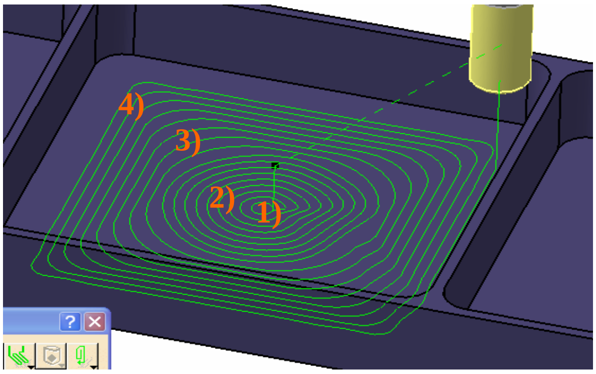


Fig.10: Spiral trajectory of a pocket

The first machining step is carried out at a speed reduced to 450 in/min. The tool begins in slotting mode and as a result, the slowdown is entirely applied (75% * 600 in/min = 450 in/min). The central spiral is then determined by a constant cutting thickness, hence the 600 in/min lead speed. The rest of the trajectory which needs to adapt to the geometry boundary has a variable cutting thickness and a speed suitable for this thickness. Geometrically, a rectangular-shaped pocket has 4 corners where the cutting thickness will be at its maximum. This results in undulations of the lead speed as can be seen in Figure 9.

The following section presents some application examples of the Visual Basic macro in commercial software (CATIA). It shows the generation of adaptive spiral trajectories for the machining of pockets of various shapes.

## 5. Application example of adaptive spirals within CAD software

The machining procedure which is programmed using the VisualBasic language, within the CATIA CAD/CAM application software, allows generating an adaptive spiral tool path for pockets of various shapes typically found for aircraft parts. The following sections describe the tests performed on a real part and the corresponding results.

### 5.1 Machining test involving a typical aerospace structural part

An implementation of the spiral cutting strategies was conducted for the machining of an entire aerospace structural part including 9 pockets (Figure 11).In this example, the "adaptive spiral" cutting paths are compared against the "conventional" type of tool paths commonly found in different CAD/CAM systems (Figure 12).

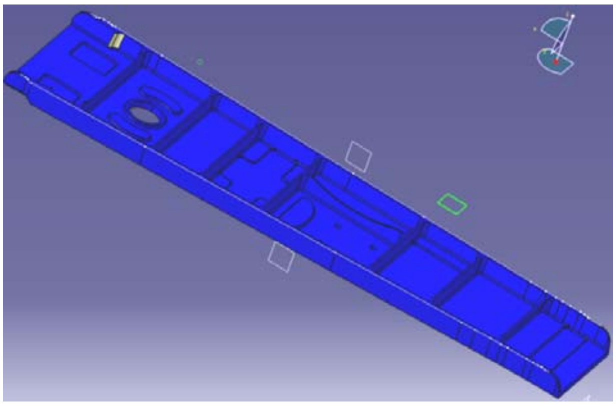

Fig. 11: Aerospace part

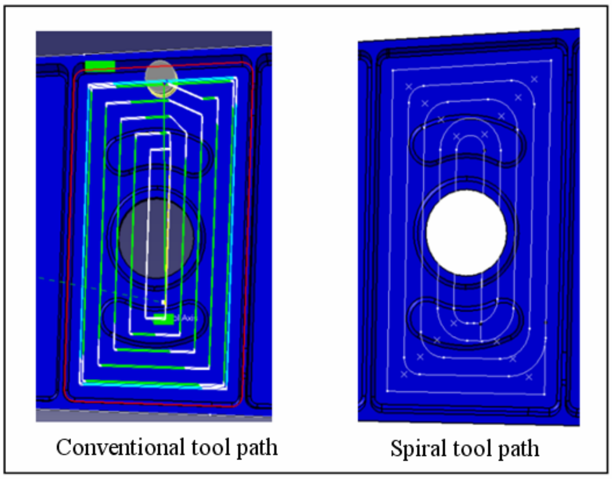


Fig.12: Conventional path and spiral tool paths

The machining test was conducted on a CNC machine tool to estimate the time reduction resulting from the new strategies as compared to the conventional paths. The time saved by resorting to this machining operation was reduced by more than 16%.

### 5.2 Pockets with inclined walls

When pockets with inclined walls are machined, the tool path is sometimes generated by using the geometry of the pocket's bottom surface (see Figure 13). The roughing sequences do not allow machining the excess material located above the inclined wall or outside the extruded bottom. For those cases, alternative or additional machining sequences are required.

The spiral tool path takes into account for the presence of inclined walls and adapts the trajectory, in order to remove the excess of material. Figure 14 shows how the trajectory needs to be generated should there be inclined walls defining the pocket.

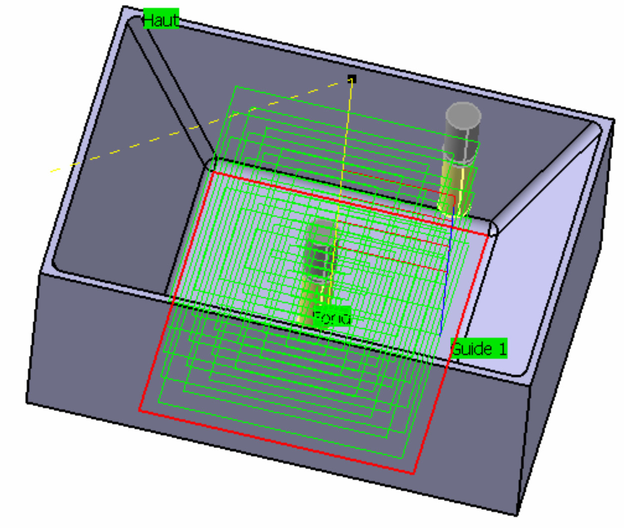


Fig.13: Inclined cutting trajectory

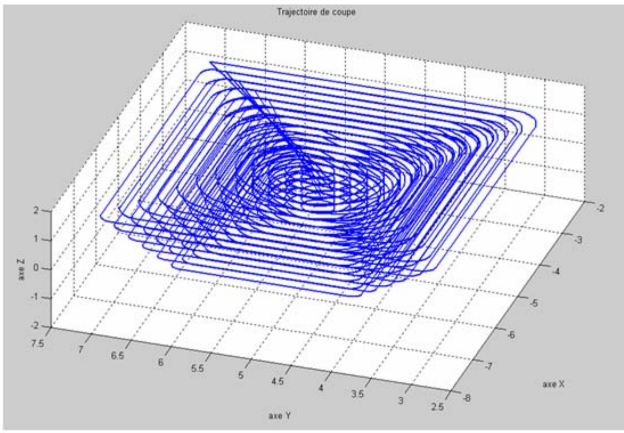


Fig. 14: Enhancement of an inclined pocket cutting trajectory

By specifying the pocket's top and bottom dimensions, the algorithm can now determine a number of axial steps to be performed and compute the boundary geometry by generating several intersection plans with the part. Once the boundary geometry is well defined at each step, the program works as described in the previous sections and draws a spiral trajectory which is adapted to all cutting thicknesses.

## 6. Conclusion

The development of the adaptive spiral machining procedure optimizes the cutting strategies in CAD/CAM software applications. This new approach significantly reduces machining time. As opposed to the traditional parallel circle method, the spiral trajectory technique reduces the time waste caused by the acceleration and deceleration of the machine axes when sudden direction changes occur.

Depending on the pocket geometry, the new spiral technique leads to a reduction in machining time by approximately 15% for the roughing operations that are involved in the manufacturing of aircraft wing components. Furthermore, the generation of spiral trajectories on a prototype part as well as a virtual machining simulation, have shown its usefulness in an industrial context.

The program, which generates the spiral trajectories, was used for various pocket geometries that are commonly found in the industry. Although the machining procedure is better adapted to simple pockets, benefits can however be realized for most geometries.

The method is recommended for any pocket geometries having corner angles for which deceleration and acceleration can be reduced or eliminated using the proposed spiral trajectories.

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