CNC Deep Hole Drilling with the Quadruple Zone Technique

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Research Article

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Abstract

Generally, in CNC machining operations, drilling of holes is handled by special canned cycles available in all modern CNC controls. These cycles offer to the user, the capability of programming the required data of drilling in the form of parameters. Hole position, depth of hole, setup clearance, plunging depth and cutting feedrate are all expressed as parameters in the structure of the respective canned cycle. The specific canned cycles are intended to accommodate all drilling demands regardless of the hole’s depth. However, to achieve a successful result, when the case comes to deep holes, cutting conditions need to be adapted accordingly and dynamically as the tool advances from the top surface to the deeper levels of the hole. Unfortunately, the existing drilling canned cycles lack of similar flexible capabilities due to their standard programming framework. The present work proposes the quadruple zone technique that bypasses the limits of the existing canned cycles and offers to the operator the capability of defining different cutting conditions at four consecutive depth zones, leading in this way to an effective and smooth deep hole drilling. The technique is implemented in the form of a G-code parametric programming algorithm.

I. Introduction

Drilling operations constitute one of the most frequent and major technological operations in manufacturing industry [1]. According to Astakhov [2], an appreciated 36% of total machining time is consumed on drilling. While drilling is a relatively simple process, deep hole drilling is recognized as one of the most complex and problematic metal cutting processes [3]. Deep hole drilling (DHD) is a machining process in which the hole length to diameter ratio is greater than five [4].

DHD process has a large number of applications such as holes supplying lubricants in gear shafts, in the automotive industry in injectors for fuel supply, in various medical and surgical instruments, aircraft parts, supply holes in hydraulic and pneumatic systems, manufacturing of dies and many others applications in general mechanical engineering [5].

Three particular conditions are required for a smooth progression and successful completion of a DHD:

a) removal of chips without affecting the surface quality b) continuous coolant supply in the cutting area
c) minimization of total machining time. As the depth to diameter ratio increases the risk of tool deflection it also increases. [6]

To meet these requirements, modern CNC controllers designed and integrated in their programming capabilities special drilling cycles under specific G codes, called peck deep-hole drilling cycles. Despite the slight differences in their design by different CNC manufacturers, these cycles apply a common machining technique, the interrupted drilling process (Fig. 1). According to this, the tool is fed into the material at a certain specified depth, then it is retracted up to a predetermined level and then again it drills a further particular depth. This process is continued until the final depth is achieved [7].
Pecking drilling cycles are defined by a series of parameters the values of which are inserted in the programming stage and remain constant during the entire execution of the drilling operation. The parameters, for which the programmer is called to define, are the setup clearance (distance of tool’s end from the hole surface), the depth of the hole, the pecking depth, the retract level and the feedrate.

However, keeping the values of the above parameters, constant throughout the drilling operation, deprives the possibility of a dynamic change of the cutting conditions which would offer significant advantages in terms of the smooth progress of the cut, the surface quality and the minimization of the machining time. A first attempt in this direction was made in [8, 9], where general G-code algorithms were developed, offering to the programmer the flexibility to define different drilling parameters as the drill advances in deeper levels.

In this paper a new strategy was designed leading to an even more simple, flexible and effective programming tool for DHD. Based on the fact that, as the tool advances in deeper levels, the operation is exposed to gradually increasing risks, the total length of the hole is delimited from top to bottom in four consecutive cutting zones. The programmer has the privilege to judge and decide on the boundaries of each zone and determine the desired cutting regime per zone. Judgement criteria can be the cutting material, the type of the tool, the size of the hole, the desired precision etc. As a result, the user gains full control over the drilling progress at each individual stage.

**II. Presentation Of The Technique**

According to the proposed DHD technique the total length of the hole is divided, from top to bottom, in four consecutive zones with their respective length decreasing progressively (Fig. 2):

1. safe zone,
2. chips breaking zone,
3. chips evacuation zone,
4. high risk zone.

The basic idea is to give the CNC programmer the ability to determine both, the limits of each zone and the desired cutting conditions for each one as well. The cutting parameters determining the drilling regime and whose instant value will be programmed in each of the four zones are:

- Feedrate $F$ (mm/min)
- Spindle speed $S$ (rpm)
- Pecking depth (mm)
- Retraction distance (mm).
The criteria to decide the limits of each zone and the most appropriate values of the above parameters, in the four consecutive zones, depend on each individual case. However, in an attempt to show the usefulness of the 4-zone separation, the basic decision criteria and the resulted decisions are discussed in the next four paragraphs respectively. The criteria can be used as an advisory tool for the operator when programming a DHD.

1. Zone I – Safe zone

Decision criteria: As the ratio of length (L) to diameter (D) remains smaller than five, the hole is considered non-deep. Consequently, zone I can be delimited from the top surface and up to a length that does not exceeds five times the diameter. This zone can be considered as a non-deep hole and therefore no specific restrictions are needed. Spindle speed and feedrate are initially estimated based on general criteria of cutting material, tool type and size, surface quality, machine etc. Multiple pecks and retractions in this zone are a waste of time and serve no useful purpose. Thus, first pecking depth is set equal to the zone's depth and retraction distance to zero.

Estimation of parameters in zone I:

Q1
Length of zone I. (A length for which the ratio L / D remains smaller than 5)

Q2
Feedrate (Initial value)

Q3
Spindle speed (Initial value)

Q4
Pecking depth (equal to the length of zone I)

Q5
Retraction distance (equal to zero)

2. Zone II – Chips breaking zone

Decision criteria: Pecks and retractions are initiated with the entrance of the tool in this zone since in this zone the hole acquires the property of a deep hole. It is important to start with big pecks and go to smaller as the tool advances in deeper levels [7]. The size of the retraction has to change based on the depth of the hole. At the beginning, a little short retraction is required and is satisfactory to break the chips. At
bigger depths longer retractions are necessary, since besides the breaking of chips their extraction should also be facilitated [10]. Thus, zone II is dedicated for chips breaking, with long pecks followed by short retractions and the next zone III for chips extraction, with shorter pecks and longer retractions.

As regards the spindle speed and feedrate, reduction of their values, as the tool penetrates deeper, can be beneficial for the surface quality [4]. The reductions are also imposed as a compensatory measure to the partial loss of rigidity of the tool at deeper depths [11]. A first reduction is programmed in the current zone while even lower values are programmed in the subsequent zones.

Estimation of parameters in zone II:

Q6
Length of zone II (Reduced)

Q7
Feedrate (Reduced)

Q8
Spindle speed (Reduced)

Q9
Pecking depth (Initial big value)

Q10
Retraction distance (Initial short value)

3. Zone III – Chips evacuation zone

Decision criteria: As in the previous paragraph mentioned, the bigger the depths the longer the retractions are required to facilitate the evacuation of the produced chips. Therefore, shorter pecks and longer retractions are initiated in this zone. In any case entire retraction over the top surface should be avoided since during pecking the chips would be washed back down the hole. Spindle speed and feedrate are reduced in this zone for a second time.

Estimation of parameters in zone III:
Q11
Length of zone III (Reduced)

Q12
Feedrate (Reduced)

Q13
Spindle speed (Reduced)

Q14
Pecking depth (Reduced)

Q15
Retraction distance (Increased)

4. Zone IV – High risk zone

Decision criteria: The last deepest region of the hole included in zone IV carries the most risks for the smooth completion of the drilling process. For this reason, the pecking depth is limited to the minimum (usually 1 up to 2 mm). Retraction distance is kept the same as in zone III, while spindle speed and feedrate are reduced even more for third time.

Estimation of parameters in zone IV:

Q16
Length of zone IV (Reduced)

Q17
Feedrate (Reduced)

Q18
Spindle speed (Reduced)

Q19
Pecking depth (1–2 mm)

Q20

Retraction distance (as in zone III)

In the direction of minimizing the cycle time, all tool’s retractions and return motions after retractions should be programmed in rapid as these are non-cutting motions. Return motions should be executed in rapid up to 2 mm above the drilled depth and then continue with the programmed feedrate to avoid a violent collision of the tool tip with chips at the current hole's bottom.

Finally, provision is made for the hole’s details through five extra parameters Q21 - Q25:

Hole Details:

Q21
X coordinate of start position

Q22
Y coordinate of start position

Q23
Setup clearance

Q24
Depth of hole

Q25
Dwell

Dwell (Q25), is an intentional time delay expressed in seconds, during which, the rotating drill remains in contact with the hole’s walls at the final depth. This improves the surface quality and increases the precision.

Input values for all 25 parameters can be transferred to the control algorithm through the user-friendly control panel of Fig. 3.

In closing this section, a clarification regarding the gradual reduction of feedrate and spindle speed in the four zones is appropriate. The choice was made with the main objective of maintaining the integrity of the tool as it penetrates deeper. The selection of ideal values for these two quantities is the subject of research by many researchers who consider how their variation affects a number of factors such as roughness, radius accuracy, material removal rate, etc. [12,13], reaching conclusions that are not always
consistent with the choice made in this work. The purpose of this work is to provide the operator with a programming tool that allows him to adjust the cutting conditions at different levels of drilling and is available to accept choices different from those made here, depending on the main objective of each particular case.

III. Graphical Illustration Of The Technique

To illustrate the technique graphically, the sequential motions in each one of the 4 respective zones are appropriately designed in the graph of Fig. 4. As it can be seen, the following motions are encountered per zone:

Zone I - Safe zone:
1. A starting pecking motion equal to the length of the zone

Zone II - Chips breaking zone:
2, 3. Long pecks
2', 3'. Short retractions

Zone III – Chips evacuation zone:
4, 5. Short pecks
4', 5'. Long retractions

Zone IV – High risk zone:
6, 7, 8. Very short pecks
6', 7'. Long retractions
8'. Full retraction

IV. Implementation Of The Technique.

The technique is implemented by an algorithm that controls the motion of the drill in terms of size and cutting conditions at each individual zone. The algorithm is developed in the environment of Heidenhain control, using the advanced G-code parametric programming language provided by the specific controller. The language is analytically presented in [6], while similar languages are also available in many others controllers. Custom Macro B (by Fanuc), User Task (by Okuma), Q Routine (by Sodick), and APL (by G&L) are among the most popular.
Applying the parametric programming method, the programmer takes advantage of using variables, arithmetic and logic functions in a G-code program, in the same way as if the program was written in common programming languages such as Pascal, Fortran, Basic, C, etc.

The algorithm is developed following the flow of the diagram shown in Fig. 5. In a pre-processing step, the 25 parameters $Q_i$ are initialized according to the entries of the control panel (Fig. 3) and are formulated as a readable by the algorithm subprogram file (INIT). With the set of parameters initialized, the algorithm first calls the suitable for the hole's diameter drill and drives it to the starting position at the setup-clearance. From this point and on, the algorithm generates the motion commands (pecks/retracts) with the specified by the respective parameters, size, feedrate and spindle speed depending on the zone the drill penetrates.

The transition, from a higher zone to a next lower, occurs only after the tool reaches the final depth of the current zone. In the algorithm, this is implemented by comparing after each pair of motions (peck/retract) the current cut depth with the zone's length. The entry of the tool into a new zone is done by simultaneously updating the parameters governing the cutting regime in the zone. Full retraction of the drill to the setup clearance is performed after the last peck and time delay expiration defined in dwell parameter. The entire code of the algorithm, together with explanatory comments is given in Fig. 6.

**Vi. Tests Results**

To demonstrate the functionality of the technique, a representative deep-hole case was selected. Specifically, a 100 mm deep hole is to be drilled with a 10 mm diameter drill by the quad-zone DHD. The desired values of the 25 parameters have been entered through the control panel shown updated in Figure 7. During the pre-processing step, the panel data is transferred to an encoded file readable by the Heidenhain control as a subroutine named “INIT”. In an attempt to develop a compact and short algorithm, 4 more subroutines were developed as many as the cutting zones, with the task of transferring the corresponding values of the cutting parameters to the main program when they are called. Both, the “INIT” and the 4 additional subroutines are shown in Fig. 8.

The algorithm was tested on the Heidenhain control of a CNC milling machine. Figure 9 shows a cross section of the graphical result after running the algorithm in the available “Test Run” mode of the controller. In the snapshot shown, the tool has reached the final hole depth (100 mm) and entered the delay timing process before fully retracting to the start position.

Even more, to confirm the correct movement of the tool during the entire drilling process and specifically in each of the 4 cutting zones, the algorithm was executed in “Single Step” mode. At the end of each command, the time point (sec), the corresponding position of the tool in the vertical axis $Z$ (mm), the type (G00 or G01) and direction (upwards or downwards) of motion were recorded. The summarized results shown in Table 1 demonstrate the correct progression in the execution of the quadruple zone DHD process.
Vii. Conclusions

The Quadruple Zone Technique for CNC deep hole drilling was presented. Its main contribution is the flexibility it offers the operator to vary the cutting conditions at selected depths as a result of the hole separation into zones. The logic of the four zones arose from the particular requirements that characterize a deep hole at various levels and the need to satisfy them in time accordingly.

The implementation of the technique was achieved by the development of a parametric control algorithm. The parametric technique is an advanced programming tool available in all modern CNC controls.

Efficiency and proper functioning of the algorithm were successfully tested with a representative DHD case.

The G-code structure of the algorithm allows it to be integrated as a DHD canned cycle enriching the existing instruction set of the CNC controls.

Declarations

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Author Contributions: Both authors contributed to the study conception and design. Both authors read and approved the final manuscript.

References


Table 1

Table 1 is available in the Supplementary Files section.

Figures
Figure 1

The interrupted drilling process

Figure 2

Deep hole division into the proposed four cutting zones
Figure 3

Control panel of quadruple zone DHD
Figure 4

The sequential motions in an illustrative case of a quadruple zone DHD technique
Figure 5

The flowchart of the control algorithm
### G-CODE

<table>
<thead>
<tr>
<th>Line</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>% 4_ZONE_DHD G71</td>
<td>Program name, units in metric</td>
</tr>
<tr>
<td>N10 G30 G17 X-50 Y-50 Z-110</td>
<td>Part dimensions 100x100x110</td>
</tr>
<tr>
<td>N20 G31 X50 Y50 Z0</td>
<td></td>
</tr>
<tr>
<td>N30 % INIT.I</td>
<td>Call subprogram with initialized Q parameters</td>
</tr>
<tr>
<td>N40 T1 G17 SQ3</td>
<td>Tool call, spindle speed defined in parameter Q3</td>
</tr>
<tr>
<td>N50 M3</td>
<td>Rotation ON, CW</td>
</tr>
<tr>
<td>N60 G90 G00 XQ21 YQ22 ZQ23</td>
<td>Move tool to hole position</td>
</tr>
<tr>
<td>N70 % ZONE1.I</td>
<td>Call subprogram with Zone 1 details.</td>
</tr>
<tr>
<td>N80 G01 Z-Q31 FQ32</td>
<td>Drill depth of zone 1</td>
</tr>
<tr>
<td>N90 % ZONE2.I</td>
<td>Call subprogram with Zone 2 details.</td>
</tr>
<tr>
<td>N100 G98 L1</td>
<td>Head of subroutine</td>
</tr>
<tr>
<td>N110 G91 G01 Z-Q34 FQ32 SQ33</td>
<td>Peck motion</td>
</tr>
<tr>
<td>N120 G00 ZQ35</td>
<td>Rapid retract motion</td>
</tr>
<tr>
<td>N130 G00 Z-Q36</td>
<td>Return in rapid 2 mm above drilled level</td>
</tr>
<tr>
<td>N140 G01 Z-2</td>
<td>Return with federate at exact drilled level</td>
</tr>
<tr>
<td>N150 D02 Q37 P01 Q31 P02 Q34</td>
<td>Update remaining depth</td>
</tr>
<tr>
<td>N160 D00 Q31 P01 Q37</td>
<td></td>
</tr>
<tr>
<td>N170 D10 P01 Q37 P02 0 P03 1</td>
<td>If not equal to zero jump to subroutine head</td>
</tr>
<tr>
<td>N180 G98 L0</td>
<td>End of subroutine</td>
</tr>
<tr>
<td>N190 % ZONE3.I</td>
<td>Call subprogram with Zone 3 details.</td>
</tr>
<tr>
<td>N200 L1</td>
<td>Call subroutine</td>
</tr>
<tr>
<td>N210 % ZONE4.I</td>
<td>Call subprogram with Zone 4 details.</td>
</tr>
<tr>
<td>N220 L1</td>
<td>Call subroutine</td>
</tr>
<tr>
<td>N230 G4 FQ25</td>
<td>Dwell at final depth</td>
</tr>
<tr>
<td>N240 G90 G00 ZQ23</td>
<td>Full retraction at setup clearance</td>
</tr>
<tr>
<td>N250 M30</td>
<td>Program end</td>
</tr>
</tbody>
</table>

### Figure 6

The G-code parametric control algorithm for DHD
Figure 7

The control panel updated with the test parameter values
Subprogram: INIT I

List of the subprograms
Figure 9

Simulation test: The drill at final depth executing the dwell command

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.docx