SINGLE PASS METAL-CUTTING OPTIMIZATION, PART 1: WITH GEOMETRIC PROGRAMMING APPROACH

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SUMMARY

This paper presents an algorithm based on the geometric programming approach for metal-cutting machining variables optimization. The approach is applied for single-pass operations. The cost is the objective minimization function and subject to machining constraints such as machine power, surface finish qualities, etc. The proposed algorithm will be integrated into CNC tool path simulation program which is developed for TOFAŞ automotive factory.

ÖZET

Tek pasolu metal kesme işlemlerinin geometrik programlama yaklaşımıyla optimizasyonu

Bu makalede, metal kesme işlemlerinde makina değişkenlerinin optimizasyonu anlatılmıştır. Önerilen yöntem tek pasolu metal kesme işlemleri için geliştirilmiştir. Maliyetin minimize edilecek amaç fonksiyon olarak seçildiği bu çalışmada, kısıtlayıcı fonksiyonlar; makina gücü, yüzey kalite değerleri vb. şeklindedir. Sunulan algoritma, TOFAŞ otomobil fabrikası için geliştirilen CNC kesici yolu benzetimi programına entegre edilecektir.

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1. INTRODUCTION

In this research, PC based NC tool path simulation and optimisation program for turning operations is developed. The main concern of this paper is to describe the metal cutting optimisation part. In machining environment, the recommended values of machining are generally used but these are not necessarily the best or the most appropriate ones. There is a need to simulate and optimize the metal cutting process since the part production cost depends largely on machining time and NC part program preparation time. Reducing manufacturing lead time gives the manufacturers a competitive advantage in today's global market. To utilize the advantages of using NC machines, the machining parameters must be optimal ones and nonproductive time must be decreased by means of off-line tool path simulation. This research is carried out for TOFAŞ automotive factory and it has two levels which are:

Level 1: The development of interactive tool path simulation CAD program.

Level 2: The optimization of machining variables of metal cutting.

This paper describes the proposed algorithm for level 2 which will be integrated into level 1. The algorithm presented here is intended to optimize single-pass metal cutting case. A numerical example case study is given to show the applicability of the proposed method. The simulation program of Level 1 provides an efficient support for user to interactively generate and view tool paths for machining a part (see Fig. 1). It is faster than manual way of producing tool paths. The tool paths can be checked for correctness and can be edited. The user can select the required tools from tool library (see Fig. 2 and 3). An additional program option is proposed to permit the operator to use optimization results of metal cutting parameters.

2. LITERATURE REVIEW

There has been a considerable number of researchers using various techniques to determine the optimum machining variables for metal cutting.(1-7) There is no one best solution technique that can be described as a universal one for metal cutting problem. Several techniques can be used but they must all cope with nonlinearities in the cutting equations and nonlinear constraints of machining. Some researchers used iterative techniques for the optimization of machining variables.(2,3) In these techniques, the initiation parameter of the solution procedure was estimated and the search was carried on using this parameter to satisfy the boundary limits of the constraints and to satisfy the machining requirements in order to determine the other parameters of the problem. These kinds of iterative procedures, which are intuitive, suffer problems as optimization techniques because the efficiency of convergence not guaranteed and it requires several trial attempts to reach the optimal solution. There is a considerable advantage in being able to transform a function.

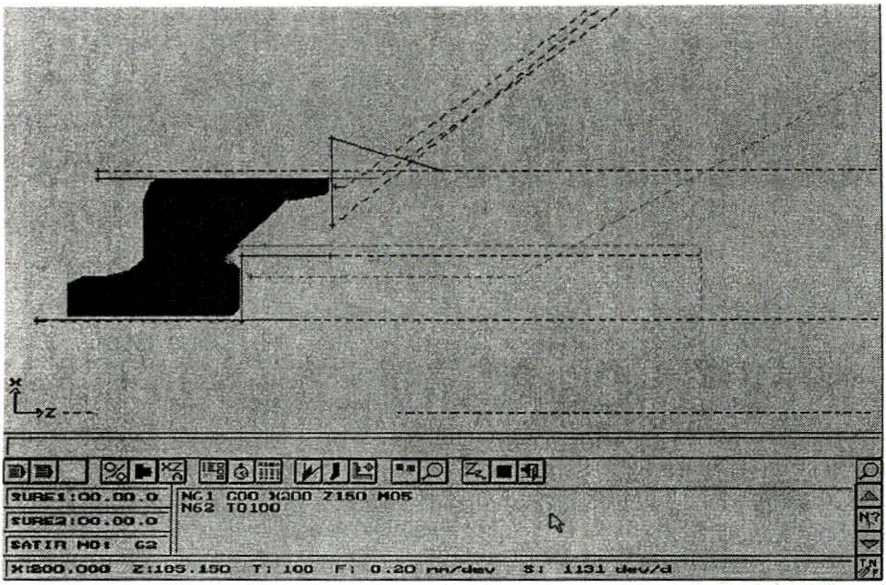
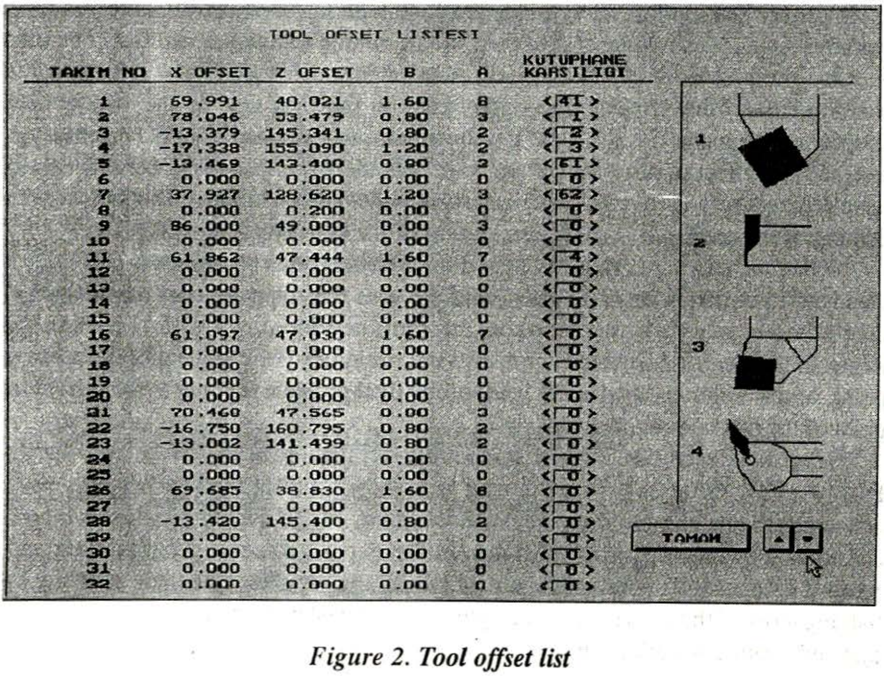


Figure 1. Tool path simulation for a turning operation of workpiece



TOOL OFSET LISTESI

TAKIM NO	X OFSET	Z OFSET	B	A	KUTUPHANE KARSILIGI
1	69.991	40.021	1.60	8	< 41 >
2	78.046	53.479	0.80	3	< 1 >
3	-13.379	145.341	0.80	2	< 2 >
4	-17.338	155.090	1.20	2	< 3 >
5	-13.469	143.400	0.80	2	< 61 >
6	0.000	0.000	0.00	0	< 0 >
7	37.927	128.620	1.20	3	< 62 >
8	0.000	0.200	0.00	0	< 0 >
9	86.000	49.000	0.00	3	< 0 >
10	0.000	0.000	0.00	0	< 0 >
11	61.862	47.444	1.60	7	< 4 >
12	0.000	0.000	0.00	0	< 0 >
13	0.000	0.000	0.00	0	< 0 >
14	0.000	0.000	0.00	0	< 0 >
15	0.000	0.000	0.00	0	< 0 >
16	61.097	47.030	1.60	7	< 0 >
17	0.000	0.000	0.00	0	< 0 >
18	0.000	0.000	0.00	0	< 0 >
19	0.000	0.000	0.00	0	< 0 >
20	0.000	0.000	0.00	0	< 0 >
21	70.460	47.565	0.00	3	< 0 >
22	-16.750	160.795	0.80	2	< 0 >
23	-13.002	141.499	0.80	2	< 0 >
24	0.000	0.000	0.00	0	< 0 >
25	0.000	0.000	0.00	0	< 0 >
26	69.685	38.830	1.60	8	< 0 >
27	0.000	0.000	0.00	0	< 0 >
28	-13.420	145.400	0.80	2	< 0 >
29	0.000	0.000	0.00	0	< 0 >
30	0.000	0.000	0.00	0	< 0 >
31	0.000	0.000	0.00	0	< 0 >
32	0.000	0.000	0.00	0	< 0 >

Figure 2. Tool offset list

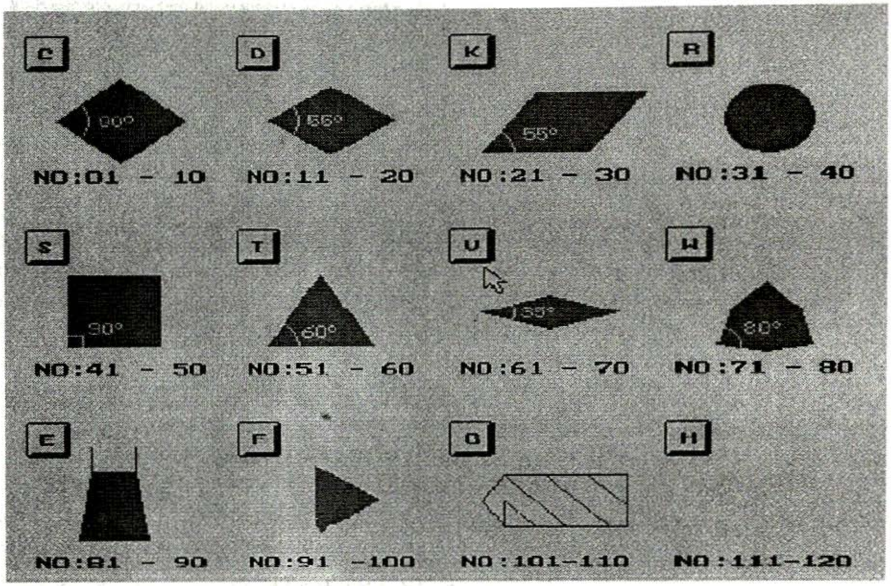


Figure 3. Cutting tools library

To convert the optimization problem to one with linear objective and constraints has advantages because one of the linear programming techniques can easily be used to solve the problem.(4,5) Because of most of the techniques have difficulties in transformation, they are not always preferred in practice. One of the widely used transformation method is the SUMT (sequential unconstrained minimization technique).(6) The effect of different starting values in the technique showed that it can lead to different results for machining variables, especially in milling. The major shortcoming of the approach is the determination of the penalty parameters.

Another technique which is developed for different types of nonlinear problems is Geometric Programming.(7-9) The technique uses the computational advantages of dual-primal equality which is based on theorems developed by Duffin, Peterson and Zener. In the case of polynomial problems the stationary point is the global optimum point. At this point, the maximum point of the dual problem is equal to the minimum point of the primal program.

Of the above methods, the best compatible techniques are SUMT and Geometric Programming. Geometric Programming is a more efficient method because of its convergence rate and the computational efficiency of the duality program which is constrained by linear equality functions. In this paper, geometric programming approach is proposed to optimize single-pass machining variables since it is suitable, satisfying most of the above mentioned points concerned with experience, transformation and control of optimization.

3. PROBLEM FORMULATION

The mathematical model of metal cutting cost in terms of the machining variables (speed, feed, depth of cut etc.) is as shown below:(10)

$$\text{Cost} = \sum C_i \quad i = 1, \ldots, n \qquad (1)$$

where the cost components Ci can be expressed as:

$$C = C_i v^{a_{i1}} f^{a_{i2}} d^{a_{i3}} \qquad i = 1, \ldots, n \qquad (2)$$

where
Ci=cost component coefficients
v=machining speed
f=machining feed
d=cutting depth of cut
a_{i1}, a_{i2}, a_{i3}=machining variable exponents
aij are arbitrary real numbers.

The objective function Eqn. 1 is called a posynomial, which is a polynomial with positive term coefficients. In practice the choice of variables for machining operations can vary considerably due to the many constraints that are applied such as maximum feed, speed, power or surface finish. The constraints can be expressed in polynomial form as shown below:

$$B_n = b_n v_n^{a_{m1}} f_n^{a_{m2}} d_n^{a_{m3}} \qquad n = 1, \ldots, N \quad m = 1, \ldots, M \qquad (3)$$

where
b_n= term coefficients of constraints
M= number of terms in constraint n
N= total number of constraints
The most common form of expression is

$$\sum_{m=1}^{M} b_n v_n^{a_{m1}} f_n^{a_{m2}} d_n^{a_{m3}} \leq 1 \qquad (4)$$

4. THE GEOMETRIC PROGRAMMING METHOD

The mathematical statement of the geometric programming program is:

$$\text{Minimise } y_o = \sum_{t=1}^{T_0} C_{0t} \prod_{n=1}^{N} x_n^{a_{0tn}} \leq 1 \quad (5)$$

subject to the constraints

$$y_m\{x\} = \sum_{t=1}^{T_m} C_{mt} \prod_{n=1}^{N} x_n^{a_{mtn}} \leq 1 \qquad (5)$$

$$x_n > 1$$

where

N is the number of independent variables

M is the number of constraint functions

T_o is the number of terms in objective function $y_o(x)$

T_m is the number of terms in the m^{th} constraint $y_m(x)$

C_{ot} are the constant coefficients in the objective function t^{th} term

C_{mt} are the constant coefficients in the m^{th} constraint and t^{th} term constraint term

a_{otn} are the exponents of independent variables in the objective function as t^{th} term and n^{th} variable

a_{mtn} are the exponents of independent variables in the m^{th} constraint as in the t^{th} term and n^{th} variable.

If the coefficients c_{ot} and c_{mt} together with constraints are positive, then Eqn. 5 defines the primal program. The primal program is the minimization of the nonlinear objective function with the nonlinear constraints.

The dual program corresponding to the above primal program:

$$\text{Maximisey : } P(W) = \prod_{t=1}^{T_0} \left(\frac{C_{ot}}{w_{ot}}\right)^{w_{ot}} \prod_{t=1}^{T_m} \left(\frac{C_{mt}}{w_{mt}}\right)^{w_{mt}} \prod_{m=1}^{M} Z_m^{z_m}$$

where

$$Zm = \sum_{m=1}^{Tm} W_{mt}$$

$$T = To + \sum_{m=1}^{Tm} T_m$$

Subject to

$$\sum_{t=1}^{To} W_{ot} = 1$$

$$\sum_{m=0}^{M} \sum_{t=1}^{Tm} a_{mnt} \, w_{mt} = 0$$

n=1, ...,N
where
$w_{mt}>0$ m=0,......,M
t=1,........,T_m

W_{mt} are the dual variables of m^{th} function and t^{th} term of function
P(W) is the dual program.

The sufficiency of the equivalence relation between the minimum point of the primal program and the maximum point of the dual program is obtained using the geometric inequalities. Duffin and Zener developed the duality theory showing that the minimum point of a convex primal program over the convex set is equal to the maximum point of the concave dual program over the convex set (set refers to the constraints). The Lagrangian and Kuhn-Tucker sufficiency conditions can be used to test that the solution will converge to an optimal one.(9)

5. APPLICATION OF GEOMETRIC PROGRAMMING TO MINIMUM COST ANALYSIS

The metal cutting cost function in terms of the machining variables (feed, speed, depth of cut etc.) can be expressed functionally by the polynomials shown below:

$$\text{Cost} = X(T_1 + T_2 + T_3 T_2/T) + y\, T_2/T \qquad (7)$$

In the case of turning, the variables in Eqn. 7 are as follows:
x=operating cost of machining involves also the labor and overhead cost rates
T_1=non-productive time
T_2=machining time per part
T_3=tool changing time per part
T=tool life
y=tool cost of cutting edge
and the cutting time T_2 is given by:

$$T_2=\pi DL/12vf \qquad (8)$$

where

D=workpiece diameter
L=length of cut

v=cutting speed
f=feed
The tool life equation is given by:

$$T = Kv^{-1/n}f^{-1/n1}d^{-1/n2} \qquad (9)$$

where
K=constant
$n, n_1, n_2 =$ exponents of machining variables of tool life, which depend on material properties of tool-workpiece combination
Substituting Eqns. 8 and 9 into Eqn. 7, the cost objective function per part is:

$$C = C_1 + C_2\, v^{-1}f^{-1} + C_3 v^{-1/n}f^{-1/n1}d^{-1/n2} \qquad (10)$$

where
$C_1=xT_1$
$C_2=x\pi DL/12$
$C_3=\pi DL(xT_3+y)/12K$

6. SINGLE PASS METAL CUTTING

In the single-pass case the depth of cut is fixed so that the objective function Eqn. 10 can be expressed functionally for a single pass turning operation as follows:

$$C_T = C - C_1 = b_1 v_1^{a11} f_1^{a22} + (b_2 d^{a23}) V_1^{a21} f_1^{a22} \qquad (11)$$

$$C_T = b_1 v_1^{a11} f_1^{a12} + b_3 v_1^{a21} f_1^{a22}$$

subject to:
$(B_j d^{aj3}) v_1^{aj1} f_1^{aj2} \leq 1 \qquad j = 1, \ldots, n$
or
$C_j v_1^{ajl} f_1^{aj2} \leq 1 \qquad j = 3, \ldots, n$

The constraints of Eqn. 11 are:
- the maximum cutting power available
- the machine-tool speed restrictions
- the machine-tool feed restrictions
- the surface finish requirements

The above constraints are the ones most generally used, however further restrictions on the machining can be added to the primal program if required without affecting the solution algorithm.

7. SINGLE PASS METAL CUTTING EXAMPLE

For the turning process, eqn. 11 can be expressed in the form:

$$C = C_1 + b_1\ v_1^{a11} f_1^{a12} + b_2\ v_1^{a21} f_1^{a22} \qquad (10)$$

where

C1=XT1

b1= xπDL/12

b3=πDL(xT$_3$+y)/12K

a_{11}= -1 $\quad$ a_{12}= -1 $\quad$ a_{21}= 1/n-1 $\quad$ a_{22}= 1/n1 -1

subject to:

$$B_j\ v_1^{aj1} f_1^{aj2} \leq 1 \qquad j = 3, \ldots, n$$

where the tool life is

$$T = K / (v^{1/n} f^{1/n_1})$$

In turning of a workpiece of length L=203 mm, diameter D=152 mm with depth of cut d=5.08 mm is considered. The other data related to cost terms is taken from R. Gupta et al. (11) The constraints for this turning operation are as follows:

$f \leq 2.54$ (feed mm / rev)

$0.015023 v^{-1.52} f^{1.004} d^{0.25} \leq 12.7$ (surface finish µm)

$0.0499 v^{0.95} f^{0.78} d^{0.75} \leq 20$ (power h. p.)

The exponents of the variables are:

A(1,1) = -1	A(1,2)= -1	A(2,1)= 3	A(2,2)= 0.16	A(2,3)= 1.14
A(3,1) = 0	A(3,2)=1	A(3,3)= 0	A(4,1)= -1.52	A(4,1)= -1.52
A(4,2) = 1.004	A(4,3)=0.25	A(5,1)= 0.95	A(5,2)= 0.78	A(5,3)= 0.75

The optimum machining variable results of the problem are computed as follows:

Optimum speed = 44.03 m/min

Optimum feed = 2.54 mm/rev

8. CONCLUSION

The problem of solving for the cutting variables was converged to the optimum using the geometric programming technique so that the optimum operations are determined. Geometric programming solved the optimization problem with little difficulty. It will cope with the nonlinear structure of the cutting objective and inequality constraint terms. The main advantage of geometric programming is the translation of a nonlinear program into a linear one with weighted function terms suited to cutting process. This enhanced the efficiency of this optimization technique compared to other techniques.

The analysis described in this paper is derived primarily for the turning process. The technique can also be applied to a wide range of processes: turning, milling, drilling, tapping, etc.

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