AN OPTIMIZATION APPROACH FOR PRODUCTION TIME MINIMIZATION IN LONGITUDINAL TURNING

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Abstract: One of the ways for increasing turning efficiency and economics is formulation and solving optimization problems through the use of mathematical models and optimization methods and algorithms. Ability to deal with complex and multi-dimensional optimization problems resulted in the use of a number of different optimization methods and algorithms for solving turning optimization problems, formulated either as single or multi-objective optimization problems with or without constraints. This study promotes the use of conceptually simple and parameter free optimization approach based on the use of exhaustive iterative search. To this aim optimization problem of single-pass turning process was considered. The proposed optimization approach was employed for determining optimal turning conditions, in terms of cutting speed, feed rate and depth of cut, so as to minimize total production time while considering four non-linear constraints. The obtained optimization solutions were compared with those obtained by the previous researchers using different meta-heuristic algorithms including genetic algorithms, simulated annealing, particle swarm optimization, differential evolution etc.

Key words: turning, optimization with non-linear constraints, production time

Jedan optimizacioni pristup za minimizaciju vremena obrade kod uzdužnog struganja. Jedan od načina za povećanje efikasnosti obrade struganjem je formulisanje i rešavanje optimizacionog problema korišćenjem matematičkih modela, kao i algoritama i metoda optimizacije. Proteklih godina razvijen je veliki broj različitih algoritama i metoda za rešavanje brojnih problema optimizacije, uključujući jednokriterijske i višekriterijske sa ili bez ograničenja. Ovaj rad promovise primenu konceptualno jednostavnog, bezparametarskog optimizacionog pristupa zasnovanom na primeni algoritma iterativnog pretraživanja. U tu svrhu razmatran je problem optimizacije uzdužnog struganja za jedan prolaz alata. Cilj je bio da se odrede optimalne vrednosti brzine rezanja, dubine rezanja i koraka kako bi se minimizovalo vreme obrade, uzimajući u obzir i četiri nelinearne funkcije ograničenja. Dobijeni optimizacioni rezultati su upoređeni sa rezultatima autora koji su primenjivali različite metaheurističke algoritme kao što su genetski algoritam, simulirano kaljenje, optimizacija rojem čestica i dr.

Ključne reči: struganje, optimizacija sa nelinearnim ograničenjima, vreme obrade

1. INTRODUCTION

As in other machining process operations, optimization of turning parameters is of great importance. Since adequate turning condition setting can directly minimize production cost and maximize productivity, while satisfying quality and process requirements at the same time, optimization of turning process represents an active field of research. In a given turning operation, optimization aims at selecting the most desirable set of turning parameter values for cutting speed, feed rate and depth of cut so as to obtain maximum productivity (or minimal production time), minimal production cost (or maximal profit) or achieve a certain balance between selected objectives. In some broader optimization problem formulation necessity to include certain constraints, such as allowable machine tool power, cutting tool life, required surface roughness of the workpiece, allowable cutting force, temperature etc., arises. A central place in the optimization process formulation represent mathematical models devoted to establishing relationships between turning parameters (independent variables) and objectives (turning performances).

Upon development of these models, either

analytically, empirically or combination of both, these mathematical models are used for formulation of different types of optimization problems including single-objective as well as multi-objective with and without constraints. So far, for solving complex turning optimization problems with several non-linear constraints, a wide spectrum of optimization methods and algorithms has been proposed. Early work in the field of turning process optimization was based on the use of analytical approaches, differential calculus and application of Lagrange multipliers method [1]. Later on, a number of researchers focused on the application of linear, non-linear, geometric, dynamic and goal programming methods [2]. Optimization of parameters in turning process with the use of Nelder Mead simplex search method was discussed by [3]. Mesquita et al. [4] applied Hooke-Jones pattern search method for optimization of multi-pass turning process. Recently, the new trend for solving turning optimization problems considers the use of meta-heuristic algorithms. Saravanan et al. [5] applied genetic algorithm (GA) and simulated annealing (SA) for optimization of turning parameters so as to minimize production time. In a related research Saravanan et al. [6] applied tabu search (TS), memetic algorithm (MA),

ant colony optimization (ACO) and particle swarm optimization (PSO) to minimize production cost. Optimization of multi-pass turning operations using ACO was also attempted by Vijayakumar et al. [7]. The turning parameters were determined by minimizing the unit production cost, subject to various practical machining constraints. Ameer and Assas [8] applied modified PSO for optimization of cutting speed, feed rate and depth of cut so as to achieve desirable compromise between the extent of material removal rate and tool wear. In order to achieve minimum production time in single-pass turning process, Bharathi Raja et al. [9] applied firefly algorithm (FA). The optimization framework was based on the optimization model proposed by Agapiou [3]. The same algorithm was later applied by Belloufi et al. [10] for determination of optimized conditions in a multi-pass turning process. The optimization problem was formulated so as to achieve minimization of production cost under a set of machining constraints. Chauhan et al. [11] applied LXPM, a real coded GA which uses Laplace probability distribution in the crossover phase, and differential evolution (DE) for determination of optimal machining conditions in CNC turning process. Chauhan et al. [12] proposed the use of totally disturbed PSO (TDPSO) for obtaining optimal turning conditions during multi-pass turning operations subject to various constraints. Mellal and Williams [13] applied cuckoo search algorithm (CSA) for minimization of the unit production cost of multi-pass turning operations. Optimization of depth of cut in multi-pass turning using metaheuristic algorithms such as GA, SA and ACO was performed by Satishkumar et al. [14]. The optimization framework was based on the optimization mathematical model proposed by Shin and Joo [15]. Srinivas et al. [16] applied PSO for optimization of multi-pass turning process so to obtain the set of cutting parameters that minimize unit production cost subject to practical constraints. In the optimization study, the mathematical model proposed by Chen and Tsai [17] was selected, which involves multiple rough cuts and a single finish cut. Optimization of multi-pass turning operations using hybrid teaching-learning-based optimization (TLBO) algorithm was considered by Yildiz [18]. The goal was to determine turning parameters considering minimum production cost under a set of machining constraints which were presented and adopted by Shin and Joo [15] and Chen and Tsai [17]. Recently, an improved flower pollination algorithm (FPA) for solving multi-pass turning optimization problem was proposed by Xu et al. [19]. Optimization model proposed by Shin and Joo [15], which takes the unit production cost as the minimizing objective and involves some practical constraints, was used to examine the efficiency of the FPA.

Although traditional optimization methods, based on the use of gradients, can produce acceptable solution, they cannot deal well with integer/discrete independent variables. On the other hand, ability of metaheuristic algorithms to deal with discontinuous, non-differentiable, and multi-dimensional turning mathematical models made them become popular for solving turning optimization problems. However, they

posses certain drawbacks, and as primary, inability to prove the optimality of the determined solution, can be listed. In that sense for solving turning optimization problems with nonlinear constraints a more robust approach may be more justified. The motivation of this study is to promote the use of conceptually simpler, and, arguably, easier for practitioners optimization approach based on the use of exhaustive iterative search. In such way optimality of the determined optimization solution would be guaranteed.

2. TURNING OPTIMIZATION PROBLEM FORMULATION

In the present study, optimization model proposed by Agapiou [3] was adopted and analyzed. Therefore, the production time (T_u), which is the sum of machining time (t_m), tool quick return time (t_R), tool changing time (t_{cs}) and workpiece handling time (t_h), was considered as objective function:

$$T_u = t_m + t_{cs} \frac{t_m}{T} + t_R + t_h \quad (1)$$

The machining time per pass is given as:

$$t_m = \frac{\pi \cdot D \cdot L}{1000 \cdot v \cdot f} \quad (2)$$

where D is workpiece diameter, L is length of the workpiece, v is the cutting speed and f is the feed rate.

Taylor's tool life equation, given by the following power model:

$$v \cdot f^{a_1} \cdot a_p^{a_2} \cdot T^{a_3} = K \quad (3)$$

where a_p is the depth of cut, and a_1 , a_2 , a_3 and K are empirical constants, can be used for estimation of tool life (T) in Equation 1.

The main turning parameters are usually specified by machinist considering past experience and tool maker recommendations. In that sense, maximum and minimum permissible values for these parameters are given as:

$$\begin{aligned} v_{\min} &\leq v \leq v_{\max} \\ f_{\min} &\leq f \leq f_{\max} \\ a_{p_{\min}} &\leq a_p \leq a_{p_{\max}} \end{aligned} \quad (4)$$

During actual turning operation, the cutting power should not exceed the maximal allowable power ($P_{\max}$) provided by the machine tool. Thus the constraint for cutting power may be given using the following empirical relationship in the form:

$$0.0373 \cdot v^{0.91} \cdot f^{0.78} \cdot a_p^{0.75} \leq P_{\max} \quad (5)$$

The tool workpiece interface temperature constraint can be given in the following form:

$$74.96 \cdot v^{0.4} \cdot f^{0.2} \cdot a_p^{0.105} \leq \theta_{\max} \quad (6)$$

where $\theta_{\max}$ is the maximal temperature of tool workpiece interface.

Due to resistance of workpiece material, the cutting force occurs in turning operations. Cutting force in turning is influenced in varying amounts of different factors including cutting parameters, tool related parameters, properties of work pieced material and environment parameters. In terms of main parameters cutting force constraint can be given as:

$$844 \cdot v^{-0.1013} \cdot f^{0.725} \cdot a_p^{0.75} \leq F_{\max} \quad (7)$$

where $F_{\max}$ is the maximal allowable cutting force.

The surface quality of turned parts is one of the most frequent customer requirements. In finishing operations, it must not be greater than the maximal specified value ($R_{\max}$). The surface roughness constraint, in terms of main turning parameters, can be expressed as:

$$14785 \cdot v^{-1.52} \cdot f^{1.004} \cdot a_p^{0.25} \leq R_{\max} \quad (8)$$

The other necessary cutting data for formulation and solving of the considered turning optimization problem, as proposed by Agapiou [3], are given in Table 1.

Parameter	Value	Parameter	Value
L	203 mm	$P_{\max}$	5 kW
D	152 mm	$\theta_{\max}$	500 °C
$v_{\min}$	30 m/min	$F_{\max}$	900 N
$v_{\max}$	200 m/min	a_1	0.29
$f_{\min}$	0.254 mm/rev	a_2	0.35
$f_{\max}$	0.762 mm/rev	a_3	0.25
$a_{p\min}$	2 mm	t_h	1.5 min
$a_{p\max}$	5 mm	t_R	0.13 min
$R_{\max}$	20 μm	t_{cs}	0.5 min

Table 1. Optimization model data

After setting the values from Table 1 and normalizing constraints, the final formulation of the considered turning optimization problem is reduced to:

$$\begin{aligned} \text{Minimize: } T_u &= \frac{30.856 \cdot \pi}{v \cdot f} + \frac{15.428 \cdot \pi}{v \cdot f} + \left(\frac{193.3}{v \cdot f^{0.29} \cdot a_p^{0.35}} \right)^4 + 1.63 \\ \text{Subject to: } g_1 &= 0.0373 \cdot v^{0.91} \cdot f^{0.78} \cdot a_p^{0.75} \leq 5 \\ g_2 &= 14785 \cdot v^{-1.52} \cdot f^{1.004} \cdot a_p^{0.25} \leq 20 \\ g_3 &= 74.96 \cdot v^{0.4} \cdot f^{0.2} \cdot a_p^{0.105} \leq 500 \\ g_4 &= 844 \cdot v^{-0.1013} \cdot f^{0.725} \cdot a_p^{0.75} \leq 900 \end{aligned} \quad (9)$$

The final turning optimization problem, as formulated in Equation 9, is the constrained nonlinear optimization problem with three continuous independent variables.

3. RESULTS AND DISCUSSION

For solving the above given turning optimization problem exhaustive iterative search algorithm, provided in the specialized software tool “BRUTOMIZER” [20] was used.

The iterative search algorithm was selected as it represents a parameter free optimization approach that only requires performing a large number of computations that are, however, executed very fast. Moreover, one can take into account technological possibilities of available machine tools in terms of setting particular permissible values for main turning parameter values. The optimization process was run on Intel Core2Duo T5800 with 4 GB RAM.

Table 2 shows the determined optimization values for cutting speed, feed rate, depth of cut and corresponding total production times.

For the purpose of optimization solutions comparison, another set of optimization solutions was determined (Table 3), given that maximal temperature of tool workpiece interface is set to $\theta_{\max}=550$ °C in constraint g_3 (Equation 6). Namely, Chauhan et al. [11] applied LXPM and DE for solving this optimization problem with modified constraint g_3 .

As could be observed from Table 2, determination of optimal values of cutting speed, depth of cut and feed rate is predominantly conditioned by the maximal temperature of tool workpiece interface constraint (g_3). In the case of solving the optimization problem with modified constraint g_3 , i.e. when maximal temperature of tool workpiece interface is set to $\theta_{\max}=550$ °C, the most critical constraint to be satisfied is related to maximal allowable machine tool power (g_1).

The optimization solutions obtained using different meta-heuristic algorithms applied by previous researchers are summarized in Tables 4-6.

As could be observed from Tables 4-6, on a first sight the use of different meta-heuristic algorithms provided a set of better optimization solutions for the considered turning optimization problem with constraints. However, after a careful analysis of the given optimization solutions and checking the given constraints as given by Equations 5-8 it turned out that many determined optimization solutions are feasible because of constraints violations. The summary is given in Table 7.

As could be observed from Table 7, it turned out that only DE managed to correctly handle given constraints, while the other meta-heuristic algorithms such as GA, SA, LXPM and PSO were not able to determine feasible solutions which satisfy all proposed conditions.

Solution	a_p (mm)	v (m/min)	f (mm/rev)	T_u (min)	g_1	g_2	g_3	g_4
1	2	109.73	0.762	2.90458	3.648	10.6	499.987	724.181
2	2.5	104.04	0.754	2.99979	4.075	12.024	499.99	854.179
3	3	105.68	0.664	3.18929	4.292	10.816	499.986	891.712
4	3.5	109.16	0.574	3.41487	4.429	9.245	499.994	897.736
5	4	113.61	0.494	3.67288	4.516	7.737	499.986	886.392
6	4.5	116.19	0.444	3.90064	4.633	6.918	499.989	894.134
7	5	119.98	0.394	4.17102	4.703	6	499.993	884.486

Table 2. The production time and corresponding turning parameter values

Solution	a_p (mm)	v (m/min)	f (mm/rev)	T_u (min)	g_1	g_2	g_3	g_4
1	2	139.26	0.762	2.779	4.531	7.378	549.995	706.907
2	2.5	129.07	0.762	2.872	4.999	8.756	546.178	842.147
3	3	121.68	0.685	3.066	4.999	9.007	532.295	899.138
4	3.5	122.69	0.585	3.319	4.999	7.889	525.91	899.466
5	4	123.62	0.51	3.576	4.999	7.027	520.469	899.388
6	4.5	124.41	0.452	3.836	4.999	6.348	515.687	899.535
7	5	125.32	0.405	4.101	4.999	5.773	511.588	898.349

Table 3. Optimization solutions obtained under modified constraint g_3

Solution	GA				SA			
	a_p (mm)	v (m/min)	f (mm/rev)	T_u (min)	a_p (mm)	v (m/min)	f (mm/rev)	T_u (min)
1	2	118.91	0.764	2.85	2	120.39	0.753	2.85
2	2.5	114.15	0.644	3.12	2.5	112.57	0.761	2.93
3	3	114.49	0.665	3.13	3	116.68	0.648	3.15
4	3.5	120.61	0.531	3.46	3.5	118.21	0.582	3.34
5	4	106.16	0.565	3.51	4	122.05	0.507	3.59
6	4.5	104.8	0.454	3.96	4.5	125.41	0.448	3.85
7	5	110.58	0.435	4.14	5	126.28	0.4	4.12

Table 4. The production time and corresponding turning parameter values given by Saravanan et al. [5]

Solution	PSO			
	a_p (mm)	v (m/min)	f (mm/rev)	T_u (min)
1	2	139.9	0.762	2.78
2	2.5	131.94	0.762	2.87
3	3	131.73	0.695	3.04
4	3.5	134.98	0.594	3.29
5	4	134.54	0.517	3.55
6	4.5	133.78	0.458	3.82
7	5	132.15	0.41	4.08

Table 5. The production time and corresponding turning parameter values given by Deep and Bansal [21]

Solution	LXPM				DE				* Corrected values
	a_p (mm)	v (m/min)	f (mm/rev)	T_u (min)	a_p (mm)	v (m/min)	f (mm/rev)	T_u (min)	
1	2	139.26	0.762	2.78	2	139.26	0.761	2.78*	
2	2.5	129.07	0.762	2.87	2.5	129.07	0.761	2.87	
3	3	122.72	0.686	3.06	3	121.56	0.685	3.06	
4	3.5	122.43	0.585	3.32*	3.5	122.61	0.585	3.32*	
5	4	134.54	0.517	3.55	4	123.53	0.51	3.57	
6	4.5	127.92	0.454	3.82	4.5	124.34	0.452	3.84*	
7	5	132.15	0.41	4.07	5	125.08	0.405	4.1*	

Table 6. Optimization solutions as given by Chauhan et al. [11] (modified constraint g_3)

Solution	Meta-heuristic algorithm				
	GA	SA	LXPM	DE	PSO
1	g_3 (516.587)	g_3 (517.663)	OK	OK	g_3 (551.005)
2	g_3 (502.783)	g_3 (516.962)	OK	OK	g_3 (551.004)
3	g_3 (516.414)	g_3 (517.665)	g_1 (5.044)	OK	g_3 (551.059)
4	g_3 (512.305)	g_3 (517.61)	OK	OK	g_3 (548.052)
5	g_4 (983.768)	g_3 (517.222)	g_1 (5.458)	OK	g_3 (539.864)
6	g_4 (918.237)	g_3 (516.423)	g_1 (5.145)	OK	g_3 (532.287)
7	g_4 (958.178)	g_3 (511.878)	g_1 (5.298)	OK	g_3 (523.847)

Table 7. Analysis of constraints violations in the determined optimization solutions by meta-heuristic algorithms

Namely, the most common method for handling linear, non-linear, equality or inequality constraints in the application of meta-heuristic algorithms is the use of penalty functions, i.e. transformation of a constrained to an unconstrained optimization problem. However, as noted by Chehouri et al. [22], the use of penalty functions necessitates the definition and proper tuning of specific metaheuristic algorithm parameters, which can be challenging and problematic.

From the analysis of determined optimization results, as well as after checking constraints violations, it is clear that the proposed optimization approach provided the best optimization solutions. As could be observed from the obtained optimization results, the metaheuristic algorithms, i.e. LXPM provided the same optimization results in the case of solution 1 and solution 2 for the modified optimization problem. Thus, one can argue that the proposed optimization approach yielded better optimization results while solving complex turning optimization problem with several nonlinear constraints. Finally, for each depth of cut, the minimal determined production times are given in Figure 1.

Fig. 1. The set of minimal permissible total production times for different depth of cuts obtained with the proposed optimization approach

From Figure 1 one can observe that in the case when maximal temperature of tool workpiece interface constraint is relaxed one reduces the total production time since higher cutting speeds are allowed. It could be also observed that with an increase in the depth of cut, there is an almost linear increase in the total production time. Although this may seem unusual, one should consider paired values for cutting speed, and especially feed rate, as well as the inevitability to satisfy the set nonlinear constraints.

4. CONCLUSION

So far a number of optimization approaches and methods were applied for solving complex turning optimization problems with constraints. This paper proposed the use of conceptually simple and parameter free optimization approach based on the use of exhaustive iterative search. The optimization model of minimization of production time in single-pass turning process was considered for demonstration of the applicability and suitability of the optimization

approach as well as to compare the optimization results with those previously obtained with the use of meta-heuristic algorithms. From the obtained optimization results it can be concluded that the solutions previously determined by past researchers using meta-heuristic algorithms were improved. It has been observed that the presented approach is able to provide reliable and feasible optimization solutions within a reasonable computational time. Optimization solutions obtained in this way can be recorded in the CAD/CAM database for automatic generation of CNC code. On the other hand, after careful and comprehensive analysis of the optimization solution obtained with the use of meta-heuristic algorithms, it turned out that a number of obtained solutions were not feasible because of constraints violation pointing out the necessity of fine tuning of meta-heuristic algorithm parameters so as to be able to handle appropriately nonlinear constraints.

Since turning optimization problems may consider non-smooth and non-convex objective functions in terms of decision variables of continuous and discrete type as well as different non-linear and linear constraints of equality and inequality type, the proposed optimization approach seems justified. Moreover, it can be easily extended for solving multi-objective constrained turning optimization problems, as well as other conventional and non-conventional machining processes such as milling, grinding, abrasive waterjet machining etc. and this is the future research scope.

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