Pergamon

International Journal of Machine Tools & Manufacture 42 (2002) 595–605

INTERNATIONAL JOURNAL OF
MACHINE TOOLS
& MANUFACTURE
DESIGN, RESEARCH AND APPLICATION

NC end milling optimization using evolutionary computation

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Received 23 October 2000; received in revised form 12 October 2001; accepted 16 October 2001

Abstract

Typically, NC programmers generate tool paths for end milling using a computer-aided process planner but manually schedule “conservative” cutting conditions. In this paper, a new evolutionary computation technique, particle swarm optimization (PSO), is proposed and implemented to efficiently and robustly optimize multiple machining parameters simultaneously for the case of milling. An artificial neural networks (ANN) predictive model for critical process parameters is used to predict the cutting forces which in turn are used by the PSO developed algorithm to optimize the cutting conditions subject to a comprehensive set of constraints. Next, the algorithm is used to optimize both feed and speed for a typical case found in industry, namely, pocket-milling. Machining time reductions of up to 35% are observed. In addition, the new technique is found to be efficient and robust. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: End milling; Optimization; Particle swarm optimizer

1. Literature survey

NC programs generated today, experience a large variation in cutting forces due to non-uniformity in metal removal along the cutter path. This may be due to a variety of factors, surface nature (curvature), tool inclination, cornering etc. In order to increase productivity, process parameters should be assigned according to the NC tool path in addition to the conditions of the part, tools, setup, and the machine. The idea is to change these variables according to the current in-process part geometry and tool path so that the cutting force is in control [1].

The current development uses experimental force data acquired by running exhaustive sample cases in 2.5 and 3-D. Such sample cases have been used by various researchers for evaluating optimization efficacy [2–4]. Tests are conducted at constant feed rates specified by the NC programmer to acquire the force variation data. Next, the force vs time data is correlated to position and the information used to insert optimized cutting parameters at the required positions (NC blocks). The modified NC program is then executed and a fresh force scenario acquired. Comparison of the two acquisitions demonstrates the efficiency of our development. Takata et al. [5] and Park et al. [6] reported the use of similar techniques for optimization implementations.

Most researchers have concentrated their efforts on modifying the feed rate alone, though some groups have tried to work with other parameters as well. All the reported efforts in the area have tried to re-schedule the feed rate per NC block instruction [1,2,7–16]. Essentially, each input NC block (either in NC or CLSF stage) is read, analyzed and then outputted with a modified feed rate code. It is the assumptions and the methods of analysis that differentiate various studies. Further, most of these studies do not address themselves to the specifics of the CNC end milling process and instead concentrate on a generic operation.

Most works on the development of NC code optimization developments involve the use of very simplistic forms of force prediction algorithms. Also, the literature shows use of volume of removed material as feedback or the machine tool horsepower as the constraint to regulate the feed rate.

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PII: S0890-6955(01)00151-1

The cutting force, as a single parameter for describing the net effect of all input variables, is found to be an optimal quantity for use as a feedback from the simulated process for feed rate optimization [8]. Simple specific energy models of metal cutting have been presented in textbooks for quite some time [17,18]. These are sometimes employed along with correction coefficients, by a number of researchers such as Wang [1], Fussell et al. [11], Lazaro et al. [19], etc.

Other more accurate models (e.g. Yellowey [20], Kline and DeVor [21], and Fussell et al. [22]) use the simple steady state milling force model by Yellowey, also known as the average cutting coefficient model implemented by Altintas et al. [23,24].

Bailey et al. [25] studied these different approaches and found the MRR approach to be adequate for estimating required spindle torque and power, but not when constraints such as chip load, maximum cutting force, deflections and chatter are considered. They also note the widespread use of static mechanistic models since, due to their closed form, they can be inverted to directly solve for the feed, which is the primary variable of concern.

The independent variables for optimal cutting parameters have been identified as the following:

- Tool diameter and length
- Number of passes
- Depth of cut (radial & axial) for each pass [26]
- Spindle speed and
- Feed (per tooth, per revolution or per unit time) [27].

Most studies state one of three objectives:

1. Minimum manufacturing cost [2].
2. Maximum production rate [26].
3. A variant of maximum productivity [5].

It has also been realized that a combination of the minimum production cost and minimum production time [28–31] is the most effective objective since neglecting either requirement alone does not do justice to the problem at hand. Agapiou [29–31] has investigated this concept extensively.

There are a variety of constraints (and various forms) that have been considered applicable by many researchers for different machining situations [32–34]. However, a comprehensive list of constraints reported in the literature is presented here:

1. Available feed and speeds (machine tool related), power, arbor rigidity, and arbor deflection [29].
2. Maximum available machine power and maximum permitted cutting edge load for roughing, and allowed maximum tool deflection for finishing [35].
3. Tool normal and tangential deflection limits [10].
4. Machine tool limiting power, spindle torque, maximum feed force, spindle speed boundaries, and feed per tooth boundaries [26].
5. Avoid excess cutting force and chatter vibration, to maintain the required machining accuracy [19].
6. The maximum cutting power available, the surface roughness required, the maximum cutting force permitted by the rigidity of the machine tool and the accuracy required, and the maximum feed rate and rotational speed available on the machine tool [28].
7. Constant cutting force, constant machining error, and the maintaining of moderate changes in cutting states [19].
8. Shank breakage and tooth breakage (limiting force and chip thickness respectively) [17].

Imani and Elbestawi [10], for example, recommend ignoring stability and maximum cutting force constraints for semi-finishing of free cutting steels.

Cutting force, once again, is found to be one of the most important process parameters used as a constraint in the cutting operation, as it relates to a large number of abnormal occurrences such as tool breakage and excess tool wear as well as basic data for estimation of chatter vibration and machining error [19].

Availability of quantitatively reliable machining performance equations relating the tool-life, forces, torque, power, surface finish, etc. to the cutting or process variables is critical to the development of an optimization algorithm [26]. It is not uncommon for researchers to forego this requirement and in some cases even assume a direct linear relation between the feed (independent variable) and the force (constraint) as well as the machining error. Such a study is presented by Takata et al. in [19]. While they report improvement in machining performance, it is easy to note that such improvement obtained is nothing more than a small portion of the possible gain. Further, in certain situations it may even result in wrong inferences leading to catastrophic tool failure conditions.

A similar approach is also reported by Weinert et al. [28]; their method of feed rate adaptation is based on the cross sectional area of the cut. While two correction coefficients have been included to account for influence of symmetry of engagement and the direction/inclination of the cut, essentially a linear relationship is assumed between the feed rate and the modified cross section parameter or MRR. However, an important addition to the literature is made by realizing that it is necessary to take into account the dynamic capabilities of the machine. The new feed-rate value must be added to the NC-file at the correct position. This is done to ensure that the calculated optimal feed rate is reached before the volume to be cut exceeds a given value. An applicable length of deceleration is calculated and included along with the cutter diameter as a safety parameter. This