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A multi-granularity NC program optimization approach for energy efficient machining

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ABSTRACT

NC programs are widely developed and applied to various machining processes. However, the lack of effective NC program optimization strategy for the machining energy efficiency has been crippling the implementation of sustainability in companies. To address this issue, a multi-granularity NC program optimization approach for energy efficient machining has been developed and presented in this paper. This approach consists of two levels of granularities: the granularity of a group of NC programs for a setup where the features are machined on a single CNC machine with the same fixture and the granularity of a NC program. On the former level of granularity, the execution sequence of the NC programs for the setup of a part is optimized to reduce the energy consumed by the cutting tool change among the NC programs. On the latter level of granularity, the execution sequence of the features in the same NC program is optimized to reduce the energy consumed by the cutting tool's traveling among the machining features. Experiments on the practical cases show that the optimization results from this approach are promising and the approach has significant potential of applicability in practice.

1. Introduction

In recent years, economic, environmental and legislative drivers have raised the energy-saving awareness of both manufacturers and customers. The soaring electricity price has brought the manufacturers the increasing energy cost which has increased by almost 70% since the late 1990s [1]. The rapidly growing production demands have incurred more manufacturing activities [2–7] where plenty of greenhouse gas has been emitted from the usage of energy sources such as electricity, coal and oil. Statistics has shown that the greenhouse gas from manufacturing accounts for more than 37% even 50% of the world's total greenhouse gas emissions [8]. In order to balance the multi-faceted dimensions of economic growth and environmental protection, a series of regulations and guidelines [9] have been developed. Additionally, the rising energy-saving awareness of customers always drives them to choose a product with lower life-cycle energy consumption. Therefore, it is imperative for the manufacturing companies to take energy saving measures to minimize their energy consumption and achieve sustainable manufacturing.

As the most widely used machine tool in manufacturing companies, computer numerical control (CNC) machines highly contribute to energy consumption in the manufacturing sector. However, statistics has shown that the energy efficiency of machines tools is generally less than 30% [10]. As thus, the optimization of numerical control (NC) machining process is of great importance for energy saving.

For any NC machining process, NC programs which are composed of a series of coded instructions are required to control it. The NC programs can be generated by not only the hand programming but also the commercial CAD/CAM packages. However, no optimal techniques have been used to optimize the NC programs to save energy. Therefore, the optimization of the NC programs used to control the CNC machines' machining processes is imperative to achieve energy efficient machining.

In order to realize energy efficient machining by optimizing NC programs, a multi-granularity optimization approach has been developed. The approach optimizes the NC programs used to control the NC machining processes from two levels of granularity: (1) the execution sequence of the NC programs used to execute all the features in a setup is optimized to reduce the energy consumed by the cutting tool change; and (2) the optimization of the tool path connecting all the machining features in the same NC program is achieved by considering the criteria of energy consumption. The

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practical cases are used to demonstrate the feasibility and effectiveness of the proposed method. The energy efficiency improvement after the multi-granularity optimization can be at least 10% which is more than 5% of the empirical value.

The rest of the paper is organized as follows. In Section 2, related work is reviewed. In Section 3, the problem description and formulation is presented. In Section 4, the multi-granularity optimization approach is presented. In Section 5, the prototype system and the corresponding implementation of our solution are presented. Finally, the research is concluded in Section 6.

2. Related work

In the last decade, the optimization for energy efficient machining, as a challenge in sustainable manufacturing [9], has attracted many researchers' attention. The related work focused on two different levels, i.e., manufacturing system and machining process.

2.1. The optimization on manufacturing system level

The research on manufacturing system level concentrates on scheduling optimization to improve the energy efficiency of the whole manufacturing system.

Mouzon and Yildirim [11] developed a multiple objective mathematical programming model and several algorithms to optimize the scheduling on a single CNC machine and reduce the energy consumption and total completion time. In order to minimize the total energy consumption and the total tardiness on a machine, a greedy randomized adaptive search algorithm was further developed to achieve the multi-objective schedule optimization. In Fang et al.'s [12] work, a new mixed integer linear programming model was built to schedule a classical flow shop that combined the peak total power consumption and associated carbon footprint with the makespan. Bruzzone et al. [13] developed an energy-aware scheduling algorithm based on a mixed integer programming formulation to realize energy savings for a given flexible flow shop which was required to keep fixed original jobs' assignment and sequencing. Dai et al. [14] presented an energy-efficient model for flexible flow-shop scheduling and an improved genetic-simulated annealing algorithm to evaluate the total energy consumption in the flexible flow shop and optimize the total energy consumption and the makespan respectively. Li et al. [9] developed a multi-objective optimization model for scheduling to improve material removal rate (i.e. MRR) and energy efficiency.

2.2. The optimization on machining process level

Different from the research on the manufacturing system level, the research on the machining process level focuses on modeling for decision making [15,16] and the optimization of the aspects involved in the NC machining processes, which mainly include the optimization of NC machining parameters [17–27] and the optimization of tool path [28–38].

In order to support decision making for energy efficient machining, some research work focuses on developing specific models of unit process energy consumption. Gutowski et al. [39] built a theoretical power consumption equation based on thermal equilibrium approach to generally describe unit process energy for machining processes. In this model, the process rate was identified as the main factor for the unit process energy consumption. However, other factors in this model, such as the fixed power P_0 and the constant k were lack of clear definition and quantification. Thus, the model cannot be used to predict the energy consumption yet. Taking up the missing specification in the model of Gutowski et al., empirical modeling approaches were adopted by Li and Kara [40] to build an empirical model to characterize the relationship between the specific energy consumption (SEC, the energy consumption of the machine tool for removing 1 cm^3 material) and the material removal rate (MRR). This model can be used to predict the energy consumption of manufacturing processes. However, it is difficult to precisely assign the factors for each coefficient of the model. In order to explore an energy consumption model with high accuracy and well-defined coefficients, a hybrid modeling approach of thermal equilibrium and empirical modeling was used to build an improved model [41]. This model was tested on a CNC micromachining center and a reliable prediction of energy consumption for given process parameters with a higher accuracy was obtained. However, the further extension of the model is still needed to achieve a more generic energy consumption model.

Simultaneously, other research work was carried out to model the energy consumption to characterize the relationship between the process parameters and the energy consumption for cutting processes and optimize the process parameters. Newman et al. [8] developed an empirical model to establish the relationship between the power consumption and the process parameters such as spindle speed, federate, cutting depth and cutting width. An experimental design method was adopted by Lin et al. [42] to establish a machining parameter optimization model of multi-pass turning operations in dry and wet cut environments. Design Expert was used to optimize the cutting parameters of the turning operation by Anand et al. [43], the optimized values were further checked and compared by those being generally used. A response surface method was used by Campatelli et al. [44] to optimize the process parameters to minimize the power consumption in the milling of carbon steel. Kant and Sangwan [45] considered power consumption and surface roughness by optimizing the machining parameters. On the basis of the experimental data obtained by the sensors mounted on the cutter, another empirical model involving spindle speed, federate and cutting depth was presented by Hu et al. [46]. In Camposeco-Negrete's work [47], the Taguchi method was used to analyze the relationship among cutting parameters, energy consumption, and surface roughness to optimize cutting parameters and achieve the minimum energy consumption and the best surface roughness. Based on weighted grey relational analysis and response surface methodology, a multi-objective method was developed by Yan and Li [48] to evaluate trade-offs between sustainability, production rate and cutting quality. In Wang et al.'s work [49], artificial neural networks were used to establish the complex nonlinear relationships between the process parameters including spindle speed, federate, cutting depth and cutting width, and energy consumption. Intelligent algorithms were then applied to identify the optimal process parameters.

In addition, the influence of tool path on energy consumption was also studied. Several tool path generation schemes were tested to explore the influence of tool path generation schemes on the amount of energy required to machine the same part [50]. The non-proportional relation between energy consumption and machining time was verified by [51]. The tool path was considered in [52] to develop a model for the energy evaluation. All these studies have indicated that tool path has a significant impact on energy saving in machining process. However, the existing research work on tool path optimization mainly aims at high-productivity machining. Much research has been done on minimizing the cutting time and the air time (i.e. the time to move spindle in the air) by optimizing tool path generation and the connection among the tool path and so on. A comprehensive survey can be found from [53].

Based on the above detailed literature survey, it can be observed:

- Energy consumption is influenced by scheduling, process parameters and tool path significantly. However, compared with