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Sequencing the features to minimise the non-cutting energy consumption in machining considering the change of spindle rotation speed

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ABSTRACT

A considerable amount of energy consumed by machine tools is attributable to non-cutting operations, including tool path, tool change, and change of spindle rotation speed. The non-cutting energy consumption of the machine tool (NCE) is affected by the processing sequence of the features of a specific part (PFS) because the plans of non-cutting operations will vary based on the different PFS. This article aims to understand the NCE between processing a specific feature and its pre- or post-feature, especially the energy consumed during the speed change of the spindle rotation. Based on the developed model, a single objective optimisation problem is introduced that minimises the NCE. Then, Ant Colony Optimisation (ACO) is employed to search for the optimal PFS. A case study is developed to validate the effectiveness of the proposed approach. Two parts with 12 and 15 features are processed on a machining centre. The simulation experiment results show that the optimal or near-optimal PFS can be found. Consequently, 8.70% and 30.42% reductions in NCE are achieved for part A and part B, respectively. Further, the performance of ACO for our specific optimisation problem is discussed and validated based on comparisons with other algorithms.

1. Introduction

According to the International Energy Agency, nearly 1/3 of the global energy consumption and 36% of carbon dioxide emissions are attributable to manufacturing industries [1], and the electricity consumption of machine tools accounts for more than half of the total U.S manufacturing electricity consumption [2]. Thus, reducing the energy consumption of machine tools during the use phase is a significant topic for both academic research [3] and industrial application [4]. The energy consumption of machine tools can be reduced by replacing the existing traditional machines with the advanced energy-efficient machines that have the energy-recycling devices [5] and the efficient power generation [6] and distribution [7] systems, but it greatly increases the financial burden on the enterprises and it is not economically sound for the enterprises to abandon the existing machines [8]. Considering economic efficiency, our research aims to reduce the energy consumption of the existing machine tools without purchasing additional energy-saving devices.

The machining energy consumption of a machine tool (MTE) accounts for a majority of its total energy consumption [2]. The MTE is defined as the energy consumed by the machine tool for completing a feasible processing plan for a specific part, which can be divided to two types: non-cutting energy consumption and cutting energy consumption of the machine tool (NCE and CE) [9]. The NCE is defined as the energy consumed for the non-cutting operations of the machine tool, including tool path, tool change, and change of spindle rotation speed [10]. Generally, the NCE

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accounts for more than 30% of the MTE [10]. The CE is defined as the energy consumed when a part is actually cut by a machine tool. It has been proved that the value of the CE is affected by the processing sequence of the features of a part (PFS) [11]. Thus, finding the PFS which results in a smaller value of CE has been confirmed to be an effective energy consumption reduction approach [12]. However, the potentiality for this approach to reduce the NCE has not been well explored. Hu et al. [13] considered both the NCE and the CE while adjusting the PFS to reduce the MTE, but the detailed model for the NCE has not been provided. Besides, the CE model is redundant for the part without volumetric interaction among the features, but it has not been identified and removed from the existing MTE model.

For the NCE, the modelling work for the energy consumption of the machine tool during tool path (TPE) and tool change (TCE) has been developed by Hu et al. [14]. The TPE is defined as the energy consumed by the machine tool for moving the cutter to the right position to begin the actual cutting and the TCE is defined as the energy consumed by the machine tool for changing and selecting the right cutter [14]. However, the energy consumption of a machine tool during the change of spindle rotation speed (SCE) has been ignored. The SCE is defined as the energy consumed by the machine tool when the spindle rotates from a low (high) speed to a high (low) speed [15]. The SCE accounts for nearly 14% of the total NCE [10] and has energy-saving potentials [15]. The SCE can be subdivided into energy consumptions of the machine tool for the spindle acceleration (ASE) and deceleration (DSE). The PFS can affect the value of the SCE within the NCE, because the difference between the spindle rotation speeds of a pair of features on the PFS can vary if any of the features is replaced by another feature. Based on this discovery, the main novelty of this paper is to reduce the NCE with the SCE included through feature sequencing, and the proposed model and optimisation approach are the main contributions. The SCE can be directly obtained by the experiment measurements according to the start and end speeds. When using this method, the experiment measurements must be conducted again once the value of the start or end speed is changed, and it is laborious. To reduce the experiment costs, it is an innovation of this paper to introduce an empirical model to predict the SCE. It should be noted that the experiment is also required to develop the empirical model, but after obtaining the model, the SCE between any two spindle rotation speeds can be predicted without further experiments. In the optimisation work, Hu et al. [13] has verified that Genetic Algorithm (GA) can effectively solve the energy-aware feature sequencing problem when the MTE is regarded as the optimisation objective. When the optimisation objective is changed to the NCE which considers the SCE, the performance of GA may become inferior. A purpose of the optimisation work delivered in this paper is to present and validate an effective algorithm for solving the new single objective optimisation problem.

Based on the above, this study aims at understanding the SCE and integrating the developed SCE model with the existing NCE model which only considered the TPE and the TCE. Then, a model to depict the NCE between processing a specific feature and its pre- or post-feature has been further developed. The single objective optimisation in this research is to minimise the NCE through finding the optimal PFS. According to preliminary studies, Ant Colony Optimisation (ACO) is employed and modified as the optimisation approach to search for the optimal PFS for its good performance in solution quality [16] and computation speed [17]. Based on the case study, the proposed approach is demonstrated and its performance is compared and validated. In this study, it is assumed that all of the required processing for a part can be finished on a single machine tool.

The remainder of the paper is organised as follows. The background and motivation are given in the next section. The problem description and the model for the NCE are presented in Section 3. In Section 4, the working procedures of ACO for solving the aforementioned optimisation problem are described. Case studies are conducted to demonstrate and discuss the developed approach in Section 5, and a brief summary and future work are given in Section 6.

2. Background and motivation

The reduction of NCE has been the topic in the previous energy-aware feature sequencing studies. For example, a mathematic model was developed to reduce the NCE, including the TPE and the TCE by adjusting the PFS [14]. However, the model ignored the SCE resulting from the difference between the spindle rotation speeds of a pair of features on the PFS. The SCE accounts for nearly 14% of the total NCE [10], and it has energy-saving potentials [15]. In related studies considering the SCE, a mathematic model was developed where the value of the SCE was assumed as a constant [18]. In addition, a feature precedence graph was generated to identify the manufacturing precedence constraints, and the value of the SCE was also assumed as a constant [19]. A main limitation of these models is that they use an inaccurate and oversimplified SCE model. For example, the value of the SCE between all pairs of features in a part has not been set to a variable that considers the actual values resulting from the required acceleration or deceleration. In fact, the SCE is dependent on the start and end speeds of the spindle rotation between the features. Moreover, the data for the SCE were made up, which weakens the accuracy of the model and skews the results.

The value of the SCE can be accurately obtained by the experiment measurements according to the start and end speeds [15]. When using this method, the experiment measurement must be conducted again once the value of the start or end speed is changed. To reduce the experiment costs, it is important to develop a SCE model to predict the value of the SCE according to the difference between two spindle rotation speeds. To obtain the SCE model, Shi et al. [20] developed a quadratic model to predict the energy consumption of a machine tool for the acceleration of the spindle rotation (ASE) from measured power data. However, the start speed of the spindle rotation can only be set to 0 rpm. To predict the ASE from an arbitrary low speed to a higher speed, a model based on the spindle torque was proposed [21]. The coefficients in the model were obtained by the experiments, and the prediction accuracy achieved 90% [21]. However, the model is unable to predict the energy consumption of a machine tool for the deceleration of the spindle rotation (DSE). A model for the DSE was developed by multiplying the torque with the angular velocity [22], but the parameters used in this model, such as friction torque, are difficult to acquire for a specific machine tool. The results of these previous studies do not yet provide a comprehensive SCE model but can be used as precursor to develop our model for predicting the SCE between processing a specific feature and its pre- or post-feature.

After developing the mathematic model, the algorithms can be employed to search for the optimal PFS which results in the minimisation of the NCE with the SCE included. Hu et al. [13] has proved that Genetic Algorithm (GA) can effectively solve the energy-aware feature sequencing problem when the MTE is regarded as the optimisation objective. When the optimisation objective is changed to the NCE, the performance of GA may become inferior. So far, the specific algorithms to minimise the NCE have received little attention. For the related time-aware feature sequencing problem, plenty of algorithms, such as deterministic algorithms and meta-heuristics, have been employed in the literature. These works can be used as references for the algorithms selection to minimise our