Energy 121 (2017) 524–532

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A novel approach for acquiring the real-time energy efficiency of machine tools

Peiji Liu, Fei Liu*, Hang Qiu

The State Key Laboratory of Mechanical Transmission, Chongqing University, Shazheng Street 174, Shapingba, Chongqing, 400044, China

ARTICLE INFO

Article history:
Received 16 January 2016
Received in revised form
31 December 2016
Accepted 9 January 2017
Available online 9 January 2017

Keywords:
Energy efficiency
Machine tools
Drive components
Energy consumption

ABSTRACT

Machine tools (MT), as the key equipment of manufacturing industry, have enormous quantity and consume great amount of energy. In order to achieve consistent improvement of energy efficiency and environmental performance in manufacturing industry, it is significant to acquire the real-time energy efficiency (REE) of MT. However, due to the unavailable parameters and the limitations of using cutting-force-measuring instruments, it is difficult for existing methods to be applied to acquire the REE of MT. This paper proposes a novel approach for acquiring the REE without any usage of cutting-force-measuring instruments. To develop this approach, a model to characterize the relationship among the REE, input power and spindle speed of MT is established based on the basic data of MT. After obtaining these basic data, this approach only requires obtaining the spindle speed and input power to calculate the REE of MT. It has been tested and validated on a common used machine tool, and the results show its practicability and high level of accuracy for obtaining the REE of MT. This approach can be applied to assess the energy efficiency of MT, to support designers to design high-efficient MT and users to improve the energy efficiency of manufacturing process.

1. Introduction

Manufacturing industry plays an indispensable role in the global economy and is responsible for over one third of global energy consumption and CO2 emissions [1]. Driven by the combination of increasingly environmental, political and economic pressures (e.g. EU 20/20/20 target [2], ISO/CD 14955-1 standardization effort [3], and also increasing energy and resource prices), the demand to reduce the energy consumption and greenhouse gases emissions of manufacturing industry is now more urgent than ever [4]. In manufacturing industry, MT, as the key manufacturing equipment, have enormous quantity and consume substantial amount of energy [5]. For instance, China has approximately 7 million MT. Assuming the average installed power of a single MT is 10 kW, it was estimated that the total energy consumption per year would reach twice more than the total installed capacity of Three Gorges Hydropower Station which is the biggest hydro power station in the world [6]. Meantime, Gutowski's [7] and Liu's [8] studies indicate significant improvement potential at the energy efficiency of MT which are less than 30%. To move toward energy efficient manufacturing, it is paramount for designers and users of MT to access detailed information about the energy efficiency of MT, thus effective acquisition of energy efficiency for MT is essential [9,10].

The first step towards obtaining energy efficiency of MT is to devise models to understand and characterize the energy efficiency. In this endeavor, there are two main models for determining energy efficiency of MT. The first one is process energy efficiency model, e.g. the specific energy consumption model of Gutowski [7] and Kara et al. [11], which is defined as the energy required to remove material per unit volume or mass. Even through the process energy efficiency is easy to be predicted using experimental method and is common used to compare the process energy efficiency differences of the same machining workpiece under different machining parameters, it can hardly be employed for supervising the real-time machining conditions. The second one is real-time energy efficiency (REE) model, e.g. Liu's model that the REE is defined as the ratio of the output power(also called as cutting power) and the input power of machine tool [12]. The REE of MT is able to provide the information of machine tool operation and tool condition not only for designers to design high-efficient MT, but also for users to optimize the manufacturing process [13]. It is also significant to assist in gathering all the information needed by

* Corresponding author.
E-mail address: fliu@cqu.edu.cn (F. Liu).

http://dx.doi.org/10.1016/j.energy.2017.01.047
0360-5442/

industrial firms in adopting technologies, as well as by policy-makers in designing appropriate policies [14,15]. However, there are no valid and handy approach for acquiring the REE of MT.

Traditionally, efforts related to obtain the REE of MT have been made on three different perspectives. From the viewpoint of material removal process, acquiring the REE of MT lies in the acquisition of cutting power, and there are three main approaches used for cutting power acquisition. Based on the principle that the cutting power is equal to cutting force multiply by cutting speed, the first one (direct-measured method) uses torque (or moment) sensor or dynamometer to measure cutting force, and the second one uses orthogonal machining theory to calculate cutting force, e.g. Merchant's [16] and Pramanik's [17] models. Whereas the third approach is to apply empirical modelling. For instance, Aggarwal's [18] and Yoon's [19] models. Apparently, both the empirical modelling methods and direct-measured methods require to install cutting force measuring instruments to carry out the cutting experiments. However, the cutting force measuring instruments not only have a high cost, but also can hardly be installed on some MT, such as gear hobbing machine. More importantly, the usage of those instruments have much negative influence on the performance of cutting tools and cannot be applied for long-term monitoring on MT. Meanwhile, the theoretical modelling are infeasible to obtain REE due to the complexity of models and variability of machining parameters for each case [11]. From the perspective of machining conditions, Draganescu et al. has established an empirical relationship between the REE of drive unit and machining parameters [20]. However, due to the complexity of MT and the variability of machining conditions, it is not validated on the whole machine tool under other processes [11]. From the perspective of additional load loss, Hu [21] and Wang [22] have established an empirical relationship among REE, input power and additional load loss coefficients. However, in order to obtain the additional load loss coefficients, the cutting force measuring instruments is necessary. Without providing the exact value for each variable and coefficient, the acquisition of REE is still infeasible.

To date, the existing acquisition methods are difficult to be applied to monitor the REE of MT for the long term. This deficiency is addressed in this paper that presents a novel approach for acquiring the REE of MT without any usage of cutting force measuring instruments. To develop the proposed method, the methodology for establishing the novel model for acquiring REE is introduced in Section 2. From the perspective of energy transmission, a novel model for acquiring the REE of MT is established by investigating the relationships among cutting power, power loss of drive components, and the variable power loss as well as input power of MT in Section 3. Then, the procedures for measuring the REE of MT are developed in Section 4. To demonstrate the accuracy and validation of the proposed approach, a case study on a common used machine tool is carried out, and the comparisons among direct-measured method, indirect-measured method and the proposed method are analyzed in Section 5. Combining with the studies in energy saving strategies of manufacturing industry, the applications of this study are discussed in Section 6 as well.

2. Methodology for establishing REE model

To obtain the REE data of MT, the conventional model of energy efficiency, shown in Eq. (1), which has two power variables (input power and output power) has been common used for many years [8].

$$\eta(t) = \frac{P_{cut}(t)}{P_{cnc,i}(t)} = \eta_{IO}\left(P_{cnc,i}(t), P_{cut}(t)\right) \tag{1}$$

From the perspective of energy transmission, the cutting power, as the efficient output power of machine tool, must have one-to-one correspondence relationship with the input power of machine tool. Therefore, the REE model in Eq. (1) can be transformed into one power variable formation, as shown in the following.

Shown as Fig. 1, the spindle system of MT is composed of frequency inverter(FI), spindle motor and mechanical transmission system(MTS).

For frequency inverter, spindle motor and MTS, their power loss are consisted by fixed power loss which is equal to its idle load power, and variable power loss which is equal to the power loss caused by its output power. As illustrated in Fig. 1, $F_i(P_{m,i})$ is the variable power loss of frequency inverter which is a function of its output power, $F_m(P_{t,i})$ is the variable power loss of spindle motor which is a function of its output power, and $F_t(P_{cut})$ is the variable power loss of mechanical transmission system which is a function of its output power.

Then, the relationship between cutting power and input power of spindle system can be expressed by the following equation.

$$P_{s,i} = P_{cut} + P_{t,l} + P_{m,l} + P_{i,l} + dE_i/dt + dE_m/dt + dE_t/dt \tag{2}$$

In addition, dE_i/dt,dE_m/dt and dE_t/dt are so small that can be omitted during steady operation process [8]. So, Eq. (2) can be written as Eq. (3):

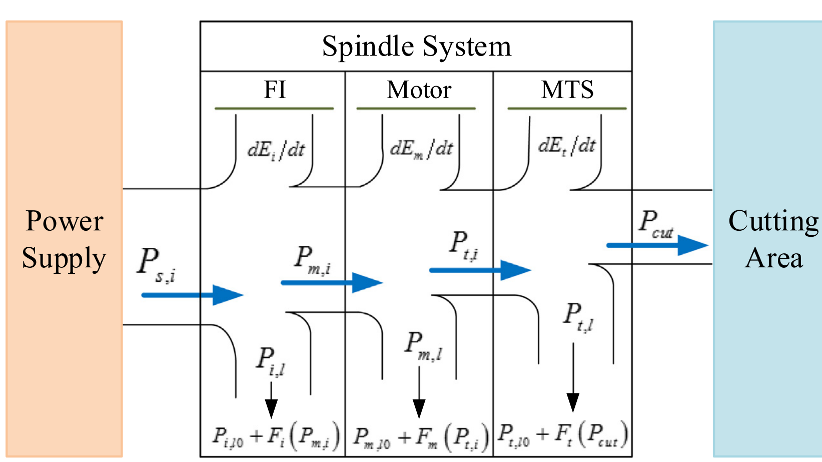

Fig. 1. The power flow for spindle system of MT.