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Analytical approach to establishment of predictive models of power consumption of machine tools' auxiliary units

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ABSTRACT

Simulation of power flow in machine tools is crucial for future development of energy efficient machines as well as for energy optimization of existing machines, production systems and manufacturing processes. This paper describes analytical approach for modelling of energy consumption of auxiliary units of the CNC machine with corresponding activity management, because these units are usually not included in current models. The developed model is then compared with the measurement of the real 3-axis machine to prove the accuracy of the model. Results show the need to calibrate the real consumption of each unit instead of theoretical value from the plate of the unit. Without this calibration, models can be inaccurate.

1. Introduction

The issue of production machine energy consumption has been recently gaining prominence, particularly due to the efforts made by the developed countries to reduce the impact of human activity on the environment. Since the operation of production machines is very energy-demanding, it is during their operation that production machines contribute to damaging the environment the most, as shown by previous studies (CECIMO, 2009). Rising energy prices together with efforts to reduce manufacturing costs have resulted in machine tool users request for minimizing energy demands of manufacturing. This pressure on production machine producers is further increased by the EU directive on reducing energy demands in all areas of human activity, in particular in industrial production, where production machines are significant energy consumers (European Union, 2009). In order to meet the objective of reducing production machine energy demands, it is necessary to consider potential energy savings already during the design stage of these machines or when planning production on these machines. Simulation of energy consumption during the design phase of the machine or technology can be an advantage giving an overview on costs of planned production which is nowadays one of the current issues. This cannot be achieved without the application of predictive models of energy consumption. A large part of studies and models that have been carried out so far focuses in particular on predicting the consumption of drives. However, the contribution of auxiliary units to total energy consumption is significant and often higher (Holkup et al., 2013). Therefore, it is necessary to deal with them in further development of energy consumption predictive models systematically and to give them the attention they deserve.

1.1. State of the art

Draganescu et al (Draganescu et al., 2003). studied the influence of cutting conditions on machine tool efficiency and power consumption. They searched for a mutual relationship between these two parameters based on practical tests. Weinert et al (Weinert et al., 2004). focused on the possibilities of reducing the amount of cutting fluid used during machining, which is one of the methods of reducing manufacturing costs. Although they did not examine the effect on energy consumption directly, they are often mentioned since their research made it possible to increase cutting speeds. This allowed reduction in manufacturing time, an essential parameter affecting machine tool consumption. Rangarajan and Dornfeld (Rangarajan and Dornfeld, 2004) were also aware of the significant role operating times play in reducing energy consumption. They focused on the optimization of cutting tool paths during machining. They also investigated the influence of

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workpiece clamping orientation on total time of machining planar surfaces. Gutowski et al (Gutowski et al., 2006). were the first to apply an exergic approach to energy consumption of manufacturing processes (exergy measures the potential of materials to do work). Based on this approach, Gutowski created a simple model of machine tool power consumption (1). This model is based on the simplistic assumption that the consumption of auxiliary units is independent of the machining process. Using tests, he also discovered that the consumption of these units may approximately constitute up to 85% of total machine tool energy consumption.

$$E = (P_0 + k \cdot \dot{v}) \cdot t \tag{1}$$

where E [Ws] is the total energy consumed by the machine tool, P_0 [W] is the idle power, k [Wsm^{-3}] is the specific cutting process energy, $\dot{v}$ [m^{3}s] is the material removal rate and t [s] is total machining time.

This research was followed by Diaz et al. (Diaz et al., 2011), who focused on identification of relationships between cutting conditions represented by material removal rate, active power requirement and total energy consumption. Kara and Li (Kara and Li, 2011) brought new insights into energy consumption of production machines. They considered the machine as a holistic system, which is able to influence its subsections. Therefore, it is necessary to deal with the relationships between these subsections as it is no longer possible to strictly divide energy consumption between the cutting process and auxiliary units as has been the practice so far. Mori et al (Mori et al., 2011). focused on the possibilities of energy savings using enhanced acceleration and deceleration control with added synchronisation of the spindle with feed axes. Their improved model included power demand for the spindle to accelerate or decelerate. Mativenga and Rajemi (Mativenga and Rajemi, 2011) focused on the selection of optimum cutting conditions with respect to cutting tool lifetime. This initiated a discussion on power consumption during tool exchange. Li and Yan (Li et al., 2013) dealt with modelling machine tool energy consumption and established a refined empirical model of machine tool active power, which achieves significantly more accurate results in comparison with predictive models of their predecessors. In their further research, they looked at multicriterial optimization of cutting conditions as a search for a compromise between material removal rate, power consumption and surface quality (Yan and Li, 2013). Avram and Xirouchakis (Avram and Xirouchakis, 2011) focused on predictive models of energy consumption using NC code analysis. A similar sophisticated model (2) was also developed by He et al. (He et al., 2012).

$$E_{total} = E_{spindle} + E_{feed} + E_{tool} + E_{cool} + E_{fix} \tag{2}$$

where E_{total} [Ws] is the total direct requirements, $E_{spindle}$ [Ws] is spindle energy requirements for the main cutting motion, E_{feed} [Ws] is feed axes requirements for secondary cutting motions, E_{tool} [Ws] is tool exchange energy requirements, E_{cool} [Ws] is energy of cutting process cooling and E_{fix} [Ws] is machine energy requirements.

The research of the above-mentioned authors was further continued by Balogun and Mativenga (Balogun and Mativenga, 2013) and Dietmair and Verl (Dietmair and Verl, 2009), who developed own advanced models of energy consumption. These models use a division of the entire working cycle according to machine regimes. Witt et al (Witt et al., 2014). developed simulation software for real-time energy consumption and manufacturing cost predictions. This software is capable of providing valuable information already in the production planning phase. It uses data from a real control system (hardware in the loop) for the prediction of energy consumption of drives. As many other authors, they are confronted with the issue of determining the consumption of a substantial part of auxiliary units, which significantly contribute to the total consumption of a machine tool.

The analysis of existing machine tool energy models leads to conclusion that consumption of auxiliary units can be higher than consumption of drives. Unfortunately not so many researchers have been interested in the precise modelling of energy consumption of machine tools auxiliary units yet. Therefore this part of the simulation should be investigated in more details.

1.2. Research aim and scope

This paper proposes an analytical approach to the establishment of predictive models of power consumption of machine tools' auxiliary units. An estimation of power consumption of auxiliary units acquired by the model described below together with the consumption of drives. Drives can be predicted using the already published models and it will provide machine tool users with insights into total energy demands during production. The main objective of using this analytical approach is an increasing of the conformity between the consumption predicted by the model and the actual consumption of a machine tool.

2. Method of modelling

In this chapter a creation process of energy models of machine tools especially of their auxiliary units will be described.

2.1. Model establishment

The evaluation of the proposed model (see Fig. 1) can be described in the following three steps:

Step 1. Analysis of all installed machine auxiliary units and their behaviour.
Step 2. Establishment of submodels of analyzed auxiliary units.
Step 3. Sum of energy flows of all auxiliary units, including the consumption of compressed air and drives.

2.2. Core of model

The core of the established model may be mathematically described by three basic equations. They express the relationship between the active power of the device and its activity (3), the above-mentioned summation of energy flows (4) and subsequent calculation of the energy consumed (5).

$$P_i(t) = A(t) \cdot P_{input} \tag{3}$$

where $P_i(t)$ [W] is the time characteristic of the active power of a given auxiliary unit, $A(t)$ [$-$] is the time characteristic of activity of a given auxiliary unit and P_{input} [W] is the required active power of a given auxiliary unit in normal operation.

$$P_{total}(t) = P_{drive}(t) + P_{air}(t) + \sum_{i=1}^{n} P_i(t) \tag{4}$$

where $P_{total}(t)$ [W] is the time characteristic of total active power of the machine, $P_{drive}(t)$ [W] is the time characteristic of active power of machine drives, $P_{air}(t)$ [W] is the time characteristic of equivalent active power of auxiliary units powered by compressed air (see Eq.