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A methodology for online visualization of the energy flow in a machine tool

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ABSTRACT

The demand of energy efficient machine tools has increased recently due to the awareness for energy efficient production in precision manufacturing. A portion of the energy supplied to machine tools is transferred to thermal losses which influence also the thermal behavior of the precision related machine tools components. Machine cooling and process cooling can prevent thermal machine tool errors. However this further requires considerable amounts of energy. Hence there is a demand to monitor the electric, thermal, fluidic and mechanical energy flows in the machine tool in order to optimize the machining process and by this increasing its energy efficiency. This study intents to propose a method which has the capability of real-time monitoring of the entire energetic flows in a CNC machine tool including motors, pumps and cooling fluid. The structure of this approach is based on categorizing the machine into subsystems and measurements of the consumers (pump, motors, . . .) power, temperature at the inlet and outlet of the pumps and current as well as the speed of the motors. The visualization is carried out by a 2D Sankey diagram, which makes it easy to understand the energetic flows in the machine tool. The methodology is verified by the rule of energy conversion which confirms the capability of this method on real-time energy monitoring of a machine tool.

Introduction

The industrial sector was in 2015 responsible for 42.5% of the global energy consumption [1]. Based on the EU legislation [2,3], energy saving in the industrial sector is mandatory for European countries to reduce negative environmental impact. The potential for energy saving in the industrial sector is estimated to be in the range of 20%–30% [4]. Companies from the industrial sector therefore must be aware of their energy consumption and improvement capabilities. Züst et al. [5] identified the operation phase of machine tools as the hot-spot of energy consumption in the machine tool's life cycle starting from raw material procurement to disposal and recycling of the machine. As the energy consumption in the machine tool is dominant, the potential energy saving is expected to be significant. Energy related research on machine tools has emerged recently as shown in Ref. [6] and [7]. It can be inferred that production has been transferred from traditional machining, which focused on process cost and time, to modern machining which focuses on being cost, time and energy efficient. For example in Ref. [8] and [9] the cutting speed is adjusted and depth and feed rate parameters are kept constant in a turning process to obtain minimum energy consumption and maximum tool life.

Inefficient energy transformation in machine tools is not only an energy cost problem but also affects the thermal behavior of machine tools and thus the dimensional accuracy of the produced parts [10]. Thermal errors are the largest single source of dimensional errors [11]. Reducing temperature gradients in the machine tool can be realized passively, e.g. by insulation methods, or actively by fluidic cooling. The provision and thermal conditioning of the cooling fluids require a considerable amount of electric energy to be supplied to the machine tool. This energy is even higher for a more precise machine tool [12]. It is therefore suggested in literature to optimize the energy consumption based on the product to be manufactured [13]. This concept requires the online monitoring and optimization of the energy flows in the machine tool. There are two aspects to be considered regarding the reduction of a machine tool's energy consumption: Increasing

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machining capacity on one hand and saving energy on the other hand [14]. It is also concluded in Ref. [12]: Being thermally stable is not enough to be successful in future machine tools market, but energy efficient machine tools will be an important criterion for customers in this market.

Recently, much effort has been carried out to obtain a method for monitoring or reducing the energy supplied to machine tools. It is also recommended to monitor and visualize energy consumption continuously to achieve energy-saving machine tools and manufacturing systems [14]. The variable energy supplied to a machine tool was monitored by measuring the input power of the spindle [15]. The authors distinguish between two characteristics: constant and variable electric power demands. The first is related to the base load of the machine in non-machining states, while the second relates to the process dependent power demand during machining. Vijayaraghavan and Dornfeld [16] used an MTConnect^{SM} software and extrapolated data from power measurements of the spindle for online monitoring of the energy consumption in the machine tool. Avram and Xirouchakis [17] applied a methodology to predict the power consumption of a milling machine based on spindle power, cutting parameters and machining strategy. All of the discussed energy monitoring methods are focused on the characteristics of cutting parameters and energy supplied to the spindle.

Two options exist to increase the energy efficiency of the machine tool, while not affecting its thermal properties behavior in a negative way: first the reduction of the amount of heat generation by better design of machine tool's components such as motors and pumps, resulting in a better energy conversion efficiency and less power demand for the cooling. Second the improvement of the cooling system unit by active controlled cooling system. If the cooling system in not controlled by feedback from the machine tool, the circuit must be adjusted if the heat sources are changed.

In this paper the approach presented in Ref. [18] is extended to be used in online monitoring applications. The online monitoring approach is capable to quantify and visualize the energetic flows and the heat sources in the machine under investigation, in real-time. In this study an energy flow model is developed on component level, which makes it feasible to be applied for different types of machine tools since the component such as pumps, motors and cooling fluid are used in machine tools design. The energy flow model is implemented in the measurement routine. This measurement routine has online access to an electric power measurement system, several temperature probes and the machine's numerical control (NC) using the FOCAS 2 interface of Fanuc. The feasibility of the online quantification of machine tools energy flow is demonstrated on the example of a five axis milling machine.

Methodology

The heat sources in a machine tool increase the temperature of a machine tool to higher than the temperature of the environment. It is therefore assumed the thermal energy is transferred by convection from the machine tool to the environment not vice versa. In this methodology input and output energy at the energy consumers are measured. The amount of thermal energy which is transferred by convection and conduction are not measured since it is assumed to be negligible compared to the input and output energy of other energy consumers. The validation of method is obtained by comparing the input energy to the consumers which must be equal or greater than output energy due to ignoring the energy which is transferred by convection and conduction.

A modular energy model for machine tools is used to apply on different machine tool types and concepts. With this approach, the datasheets information of the machine tool's components, which are generally available, enable the parametrization of the model for each component. For interaction parametrization data acquisition on component level is necessary to derive the relevant parameters from measurements such as power input and temperatures and NC readout such as speed and current of motors This procedure is in line with ISO-14955-1 [19]. A physical model integrates the inputs from datasheets, measurements and NC readout to compute the energetic flows in the machine tool.

Component models

In the following sections, the energy flow models for the relevant machine tool subsystems are introduced. The aim of these models is the characterization of the relevant energy in-flow and out-flow based on the measured variables.

Servo motors

The electrical power P_{el}, mechanical power P_{mech} and heat loss of a servo motor (3 phase — Y configuration) are calculated by

$$P_{el} = 3 \cdot I \cdot \omega \cdot k_i + 3 \cdot I^2 \cdot R_a \tag{1}$$

$$P_{mech} = 3 \cdot I \cdot \omega \cdot k_a \tag{2}$$

$$P_{loss} = P_{el} - P_{mech} \tag{3}$$

where $I[\mathrm{A}]$ is the current and $\omega\left[\frac{\mathrm{rad}}{\mathrm{s}}\right]$ is the rotational speed obtained from the NC. The model further requires several parameters: $k_i\left[\frac{\mathrm{V \cdot s}}{\mathrm{rad}}\right]$ is back electromotive force constant, $R_a[\Omega]$ is the armature resistance and $k_a\left[\frac{\mathrm{Nm}}{\mathrm{A}}\right]$ is the torque constant.

Spindle

For an AC motor which is usually used in spindles, the electrical power is obtained as

$$P_{el,s} = 3 \cdot I^2 \cdot \frac{L_h^2 \cdot R_r \cdot \omega}{R_r^2 + L_r^2 \cdot \omega} \tag{4}$$

where $L_h[\mathrm{H}]$ is mutual inductance, $L_r[\mathrm{H}]$ rotor inductance and $R_r[\Omega]$ is rotor resistance. The armature current as well as the rotation speed of the rotor is obtained from the NC.

Pump

The electrical energy supplied to the pump P_{el} can be measured. The AC motor of the pump converts this electrical power to mechanical power P_{mech}^{motor} and losses in the motor P_{loss}^{motor}:

$$P_{mech}^{motor} = \eta_m P_{el} \tag{5}$$

$$P_{loss}^{motor} = (1 - \eta_m) P_{el} \tag{6}$$

where η_m, is the efficiency of the motor.

The pump utilizes P_{mech}^{motor} and transfer it to the hydraulic power P_{fl} of the fluid while generating a certain amount of heat losses P_{loss}^{pump} in the pump by:

$$P_{loss}^{pump} = P_{mech}^{motor} - P_{fl} \tag{7}$$

The total loss in the motor and the pump is

$$P_{loss} = P_{loss}^{motor} + P_{loss}^{pump} \tag{8}$$

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