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Simulation-assisted investigation of the electric power consumption of milling processes and machine tools

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Abstract

The worldwide increase in energy prices and energy consumption in recent years have led to a redirected and increased focus on energy efficiency in the industries. This paper analyses the distribution of the electrical power consumption of the components of different milling machines. Previous experiments showed that auxiliary components like cooling and control use a major share of the total electrical energy input. In an attempt to optimise the machining process, an approach to model the power input of machining centres using an empirically generated database of the basic load and a geometric, physically based model for depicting the cutting power is presented.

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Keywords: Energy Efficiency; Sustainable machining; Simulation;

1. Introduction

The recent increase of energy consumption, prices and customer requirements regarding environmental protection all over the world have emphasized the need for energy efficiency in production processes and systems in industries. The situation is no different in Germany, where much emphasis is currently being placed on increasing energy efficiency in the industrial sector even by the Federal Government. Primary energy consumption and CO_2 emissions in the country are expected to be reduced by 20% and 40% until 2020 [1, 2]. Particularly in the industry, there are high saving potentials. This potential should be exploited by governmental funding for energy efficiency measures and legal requirements. An example for the legal requirements is the German Energieeinsparverordnung (EnEV - Energy saving ordinance), which is based on European law. This regulation sets requirements for new buildings and plant engineering [1].

One of the major problems to achieve this purpose is the lack of precise knowledge about the energy requirements of the various production processes in the industry. This also applies to milling centres, where efficiency does not only depend on the machine tool but also on the used tools and parameter values. Thus, in order to optimise the energy efficiency of manufacturing systems, it is necessary to analyse the different processes to know their behaviour [3]. Thanks to the current industrial development in the field of digitisation more sensor data will be available and usable [3]. A further economic reason to increase the energy efficiency in factories is to reduce the manufacturing costs and in so doing create a competitive advantage [1].

A further challenge is gaining adaption intelligence in the production systems. This assumes that the effects of changes in production process or systems are known before the changes are effected. Therefore, simulation systems can help gaining information without the need for carrying out complex and expensive physical trials. So far, mainly analytical and mathematical models [4, 5] as well as discrete-event simulations [6–8] are used to model the energy consumption of machine tools and their components as well as for multi-objective optimisation of machining processes [9]. Also, the specific cutting energy was investigated experimentally by using different milling tools [10] and in dependence of the tool wear [11]. Lee et al. [12] modelled the energy usage of machine spindles and feed drives in view of their frictional behaviour and electric losses. On the contrary,

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this paper deals with the simulation of the electrical power requirement of machining processes and machine tools using a geometric, physically based simulation approach coupled with an analytical database of the base load of the machine tools. Using this method, complex machining processes can be modelled based on comparatively simple replacement models, which take process dynamics and other parameters, such as process stability and workpiece quality into account. Geometric, physically based simulations allow many multi-objective virtual experiments for the analysis of the workpiece quality, process time and further data without carrying out physical trials. Using this method, time and money are saved while errors during machine runtime are avoided.

In the following, the basics of the power consumption of milling machines are described. Subsequent to this, the experimental setup and the simulation model is characterised. After that, the simulation is validated. Finally, a summary and an outlook are given.

2. Power consumption of milling machines

The power and energy consumption of cutting machine tools, especially milling machines, can be divided into the power requirements of the individual components. Previous investigations showed that a large part of the power is consumed by the control of the machine as well as by additional aggregates, such as the cooling lubricant supply, cooling of the machine, the hydraulic aggregates and the chip conveyor [5, 13–16]. Further consumers are the tool changer, the lighting, the drives of the main, possible secondary spindles and the feed drives. The efficiency of the process depends, among other things, on the material removal rate. At a high material removal rate, the proportion of the active power increases with the apparent power consumption of a machine [10]. However, the individual performance of a machine tool, its specific characteristics such as the dependence of the power need in the feed direction [17] and the tool used must also be considered. The power consumptions of different machines differ significantly in standby mode and during the process [13]. The exchange of individual components can therefore strongly influence the power and energy consumption of machine tools. However, the benefit and effort of the modernisation of machines and systems are not always obvious but can be analysed by simulations [18].

In the simulation presented in this paper, the power profile of the following elements of machine tools is illustrated by the example of three 3- to 5-axis machining centres:

- machine control, sensors, actuators and basic power consumption (lighting etc.)
- main spindle
- cooling lubricant supply
- chip conveyor

3. Experimental setup and measurements

To analyse the power consumption of milling machines, a series of experiments were carried out on three different milling machines. The characteristics of these machines are listed in Table 1. Within the scope of the investigations, full and partial grooves were milled in aluminium EN-AW 7075 and construction steel 1.0577. Both the width and the depth of the grooves were varied. Two shank cutters with a diameter of 8 and 12 mm as well as a cutter head with a diameter of 50 mm were used. For compatibility reasons, the 12 mm shank cutter was used on all three machines. During the test series, the parameters listed below were varied:

- width of cut a_e: 2-12 mm
- depth of cut a_p: 1-10 mm
- cutting speed v_c: 80-800 m/min
- tooth feed f_z: 0.025-0.22 mm

Furthermore, the electrical power consumptions of the machines were recorded. The electrical active, reactive and apparent power of the milling machines were measured at their main terminals, which represent the connection point to the electrical grid. For this purpose, a Power Analyser with a basic accuracy of ±0.1% and a maximum measurement deviation of less than one percent was used. A total of 192 experiments were carried out on the three machines, in which the processing of material was analysed. The base loads of the machines were additionally determined for the different states.

By activating single aggregates and subtracting the base load of the respective machine, the power consumption of the individual components, e.g. the cooling system and the chip conveyor, were calculated as depicted in Fig. 1. For the cooling, it must be noted that the different cooling methods were measured separately. Due to this, the power consumptions of the coolant supply and machine wash rinsing presented in Fig. 1 cannot be combined with each other.

Furthermore, the power requirement of the spindle was also investigated at different rotational speeds, with the spindle being rotated in mid-air. Herefore, the nearly constant base load of the machines (Fig. 1) was subtracted from the measured total active power of the machines. These results are shown in Fig. 2. This approach made it possible to distinguish the base load from the processing load and also to analyse the processing load separately.

Nomenclature

a_e	Depth of cut
a_p	Width of cut
f	Frequency
$\vec{F}$	Force acting on cutter (vector)
n	Rotational speed
$P_{t,meas}$	Measured total power consumption of a machine tool
$P_{t,sim}$	Simulated total power consumption of a machine tool
P_c	Cutting power
P_b	Base load power
P_s	Spindle power loss
P_t	Total power consumption
T_s	Spindle torque
v_f	Feed speed
$\vec{v}_f$	Feed speed (vector)