Modeling methods of machine tools energy consumption

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Abstract

The simulation of power flow and energy consumption of 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 the state of the art in the field of simulation and modeling of energy consumption of the machine tools. The methods of modeling are presented together with their comparison because the complexity of models and their accuracy varies considerably according to the purpose of use.

Key-words: machine tool, energy model, energy consumption, ecodesign

1. Introduction

The issue of energy modeling of the production machines has been gaining prominence in last few years, particularly due to the eforts made by the developed countries to reduce the impact of human activity on the environment. Rising of the energy prices together with eforts 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 the production machines are significant energy consumers [1].

1.1. Motivation and objectives

Main objective of this paper is to introduce some methods of machine tool energy consumption modeling to normal machine tool users and other members of professional community. Energy model of machine tools allows to predict energy consumption of machine tool which can be used for a production planning.

Today the full payment for the supply of electricity for wholesale industrial costumers in the Czech Republic is usually consists of payment for the consumed energy, ecological and other taxes and payment for the services. The last item of payment is normally calculated based on the difference between ordered and consumed energy and therefore the modeling of the energy consumption is a way to savings. It should be noted that the fee for the unconsumed energy is very often higher than the fee for the consumed energy.

2. Classification of modeling methods

Based on approach to creating the model of energy consumption we can divide this models into two or three main groups

- empirical models
- analytical models
- combined models

The empirical models are created with the use of tests on the specific machine tool on specific work piece with specific technology and under specific conditions. Thus the total consumed energy of the machine tools is usually formulated as a function of the volume of removed material. The main benefit of this approach is the simplicity of models. An adaptability to changes and a transferability between machines are great handicaps of this modeling approach because it is always necessary to perform a new set of tests which are very cost and time consuming.

The analytical models are created with use of elemental analysis of machine tool used for machining. These models usually respect a machine tool construction and real technological conditions. In comparison with empirical models, they are considerably more complicated however they have higher level of the compliance and they are able to adapt to changes of technological conditions without additional tests on real machine tool.

The combined models seek to combine the advantages and suppress the disadvantages of both previous modeling method's classes according to the purpose of use.

3. Energy model survey

For better clarity, the individual models are presented in chronological order according to development of machine tool energy consumption modeling.

For evaluation of machinery energy efficiency is typically used dimensionless indicator which represent relationship between work done and consumed energy. This efficiency indicator gives no information about utilization of power for machining and therefore physical-thermodynamic indicator of energy efficiency is used instead. This indicator is called specific energy consumption (SEC) and represents relationship between energy input and specific physical quantity of product defined by Patterson [2]. This energy efficiency indicator is usually used particularly at the policy level but it is also suitable for comparing of the machine tools. If quantity of product in previously mentioned relationship is replaced by volume of removed material, we can use this efficiency indicator for all known material removal processes.

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Draganescu et al. [3] studied the influence of cutting conditions on the machine tool efficiency and on the tangential component of cutting force. These two parameters are necessary to determine the power demand of cutting operations and then total energy consumption of machine tool as it is shown in equations (1) and (2).

$$E_{cs} = \frac{P_c}{60 \cdot \eta \cdot Z} \tag{1}$$

$$E_c = Y \cdot E_{cs} \tag{2}$$

Gutowski et al. [4] created a simple model of power consumption of the machine tool described by equations (3) and (4). This model is based on the simplistic assumption that the energy consumption of the auxiliary units is independent of the machining process. By using the tests, they also discovered that the consumption of these units may be significant as it is shown in Fig. 1.

$$P = P_0 + k \cdot \dot{v} \tag{3}$$

$$B_{elect} = \frac{P_0}{\dot{v}} + k \tag{4}$$

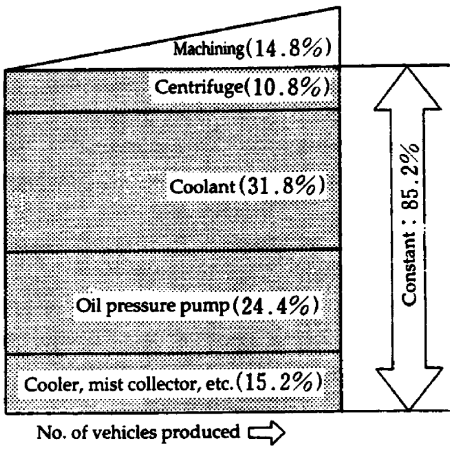

Fig. 1. *Energy used as a function of production rate for a machining line in automotive* [4]

This research was followed by Diaz et al. [5], who focused on identification of relationships between cutting conditions represented by material removal rate, active power requirement and total energy consumption. They confirm Gutowski model for establishing of SEC by tests and revealed that the machining time dominates energy demand. Their research also focused on comparing power demand of air cutting[1] and normal cutting[2]. It results in creation of simply model described in equation (5).

$$e = (p_{cut} + p_{air}) \cdot \Delta t \tag{5}$$

Kara and Li [6] also focused on identification of relationship between the energy consumption and the material remove rate. They create a model of machine tool consumption, see equation (6).

$$SEC = C_0 + \frac{C_1}{MRR} \tag{6}$$

Kara and Li tested the difference between wet and dry cut and studied an impact on specific machine coefficients in model. They found that applying of coolant requires additional energy and therefore a dry cut at the same level of material remove rate is more energy efficient than a wet cut. However for some materials the coolant allows higher material remove rate and can also improve the tool life and so it is always necessary to consider all benefits and handicaps of coolant using.

All previously mentioned models belong to category of empirical models.

Mativenga and Rajemi [7] focused on the selection of optimum cutting conditions with respect to cutting tool lifetime. That resulted in creation of energy model, which included energy consumption during tool exchanges, see equation (7).

$$E = P_0 \cdot t_1 + (P_0 + k \cdot \dot{v}) \cdot t_2 + P_0 \cdot t_3 \cdot \left(\frac{t_2}{T}\right) + y_E \cdot \left(\frac{t_2}{T}\right) \tag{7}$$

This model can be regarded as combined model, because this model reflects the energy consumption of machine tool subunit. However considerable portion of the energy consumption is established by using the already known empirical models presented above.

Avram and Xirouchakis [8] created an analytical model of energy consumption, which represents a significant progress in the field of energy consumption modeling. Their model, see Fig. 2, uses NC code analysis to establish processing time and cutting force for each milling operations. The model respects main characteristics of the machine tool that affect the calculation of mechanical motor torque and corresponding power demand of spindle and feed axes. This model also takes into account power demand of auxiliary equipment power share using resource database. Finally the predicted power requirements are integrated with respect to the processing time and provide estimation of the total energy consumption.

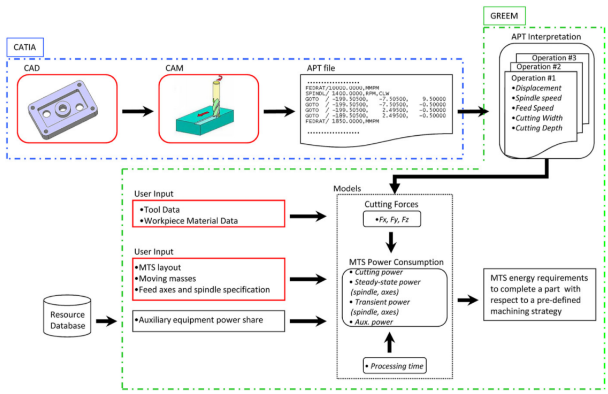

Fig. 2. *General overview of the methodology* [8]

An example of calculation of the spindle unit energy consumption is shown in equations below.

$$E_S = E_{aS} + E_{run} + E_{cut} + E_{dS} \tag{8}$$

[1] the air cutting is a machine tool operation without the interaction between tool and workpiece
[2] the normal cutting is a machine tool operation with the interaction between tool and workpiece

$$E_i = \int_t P_i \, dt \tag{9}$$

$$P_{aS} = T_a \cdot \omega = (T_{Asp} + T_{run}) \cdot \omega \tag{10}$$

$$P_{run} = T_{run} \cdot \omega \tag{11}$$

$$P_{cut} = P_{run} + P_c = P_{run} + F_c \cdot v_c \tag{12}$$

$$P_{dS} = T_d \cdot \omega = (-T_{Asp} + T_{run}) \cdot \omega \tag{13}$$

This research was followed by Gontarz et al. [9], who was inspired by previously mentioned energy model and complemented it by new auxiliary units submodels. It is worth to mention that they take into account the consumption of the compressed air respectively the equivalent electric energy consumption in their model.

$$P_{cair}(t) = C_{air} \cdot \dot{V}_{air}(t) \tag{14}$$

Balogun and Mativenga [10] also created new energy model of machine tool considering Gutowski empirical model (3), inspired by Kara and Li model (5) and using new classification of energy demand based on analysis of machine tool shown in Fig. 3. This new model of the direct energy requirements in machining is described in equation (15).

$$\begin{aligned} E_t = P_b \cdot (t_b + t_r + t_c) + P_r \cdot (t_r + t_c) + ... \\ ... + P_{air} \cdot t_{air} + (P_{cool} + k \cdot \dot{v}) \cdot t_c \end{aligned} \tag{15}$$

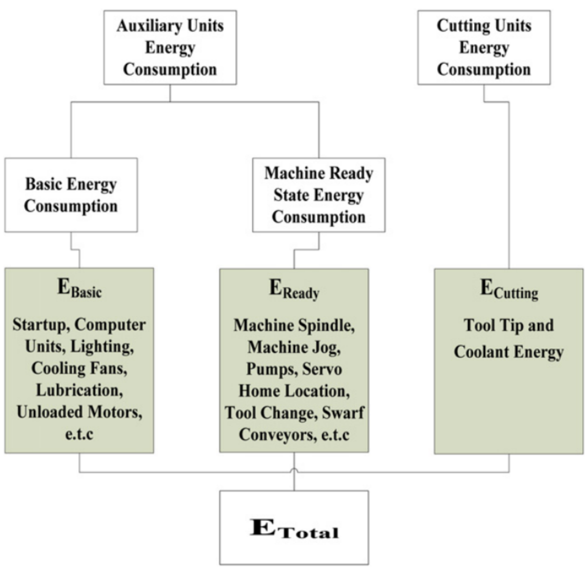

Fig. 3. *General overview of the methodology* [10]

Yan et al. [11] developed an improved empirical model of energy consumption of the machine tools inspired by the previously mentioned empirical models. In addition, this model include the spindle rotation power demand based on the power profile analysis shown in Fig. 4. The authors established a new modified equation for evaluating SEC (16), then.

[3] the main source of inaccuracy could be idle times

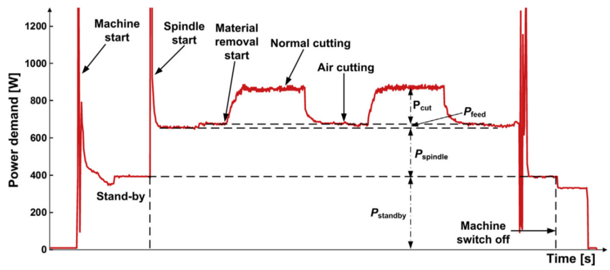

Fig. 4. *Power profile of milling process* [11]

$$SEC = k_0 + k_1 \cdot \frac{n}{MRR} + k_2 \cdot \frac{1}{MRR} \tag{16}$$

4. Models comparison

In this paper, several models of machine tool energy consumption were described.

The empirical models using SEC are very useful for predicting of energy consumption in serial and mass production and wherever it is produced a large amount of products on the same type of machine tools and under approximately the same technological conditions. Accuracy of consumed energy prediction of this models can be very satisfying (approximately about 90 %) depending on machine tool type and their utilization[3]. Some cited articles report higher accuracy which reflects the use of very simple machine tool without sophisticated auxiliary units.

Very significant progress in the field of the energy consumption modeling represent the analytical models, which use elemental analysis of the machine tool and NC code analysis bringing a very faithful production time estimation. These models have a very high compliance rate between predicted and measured power profile depending on the discretization level of the machine tool and its auxiliary units. The energy consumption can be predicted with a very high precision (approximately up to 98 %). These models can be used as a tool for looking for energy savings and optimization of the cutting conditions.

5. Conclusion

In order to meet the objective of reducing machine tools 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. So how is constantly evolving world around us evolve also production machines and therefore it is necessary to deal with modeling of energy consumption henceforth.

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Nomenclature

With respect to the authors of all mentioned models, the labelling of all physical properties was maintained. For better clarity, the properties are ordered into blocks corresponding to each of the models.

E_c	consumed energy (kWh)
E_{cs}	specific consumed energy ($\mathrm{kWh/cm^3}$)
P_c	cutting power (kW)
Y	total volume of removed material ($\mathrm{cm^3}$)
Z	material remove rate ($\mathrm{cm^3/min}$)
η	machine tool efficiency ($-$)

B_{elect}	specific consumed energy ($\mathrm{kJ/cm^3}$)
k	constant ($\mathrm{kJ/cm^3}$)
P	total power (kW)
P_0	idle power (kW)
$\dot{v}$	material remove rate ($\mathrm{cm^3/s}$)

e	energy consumption (kJ)
p_{cut}	cutting component of power demand (kW)
p_{air}	air cutting component of power demand (kW)
Δt	processing time (s)

SEC	specific consumed energy ($\mathrm{kJ/cm^3}$)
C_0	machine specific coefficient ($\mathrm{kJ/cm^3}$)
C_1	machine specific coefficient (kW)
MRR	material remove rate ($\mathrm{cm^3/s}$)

E	total consumed energy (kJ)
k	specific cutting energy ($\mathrm{kJ/cm^3}$)
P_0	power consumed by machine modules (kW)
t_1	machine setup time (s)
t_2	time taken for cutting operations (s)
t_3	tool change time (s)
T	tool life (s)
$\dot{v}$	material remove rate ($\mathrm{cm^3/s}$)
y_E	embodied energy of cutting tool (kJ)

E_S	total consumed energy of spindle (Ws)
F_c	cutting force (N)
P_{aS}	spindle acceleration power (W)
P_c	spindle power to cut material (W)
P_{cut}	total spindle power during cutting (W)
P_{dS}	spindle deceleration power (W)
P_{run}	spindle power demand on constant speed (W)
T_a	spindle torque during acceleration (Nm)
T_d	spindle torque during deceleration (Nm)
T_{run}	total friction torque in spindle (Nm)
v_c	cutting speed (m/s)
ω	angular velocity of spindle (rad/s)

P_{cair}	electric power demand of compressed air (kW)
C_{air}	specific requested power ($\mathrm{kJ/m^3}$)
$\dot{V}_{air}$	compressed air flow rate ($\mathrm{m^3/s}$)

E_t	direct total energy requirement (kJ)
k	specific cutting energy ($\mathrm{kJ/cm^3}$)
P_{air}	non cutting moves power (kW)
P_b	basic power (kW)
P_{cool}	coolant pumping power (kW)
P_r	ready state power (kW)
t_{air}	duration of non cutting moves (s)
t_b	basic time (s)
t_c	cutting time (s)
t_r	ready time (s)
$\dot{v}$	material remove rate ($\mathrm{cm^3/s}$)

SEC	specific consumed energy ($\mathrm{kJ/cm^3}$)
k_0	specific energy of cutting operations ($\mathrm{kJ/cm^3}$)
k_1	specific coefficient of spindle motor (kJ/r)
k_2	constant coefficient of machine tool (kW)
n	spindle speed (r/s)
MRR	material remove rate ($\mathrm{cm^3/s}$)

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