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MEASURE ENERGY AND CONSUMPTION

PHASE-2 PROJECT SUBMISSION

Energy Consumption Measurement with a Multichannel Measurement System on a machine tool

Keywords: energy consumption, machine tool, energy monitoring, energy using products

Abstract. Considering the energy consumption of machine tools, in the future manufactures will face not only economic and environmental, but eventually statutory challenges as well, if machine tools are subjected to the European directive on Energy-using Products (EuP). From a life cycle engineering perspective, the knowledge of energy consumption during the use phase is crucial. Currently, there is no established method of measuring the energy consumption of machine tools, and due to the variety of products, it is not obvious to propose one. A comprehensive measurement system is seen as a basis for online energy monitoring, which can be used to control the consumption of energy and costs from a TCO-point of view and to provide overall less energy consuming production methods with higher reliability.

The used measurement system was implemented on several machine tools to determine the main energy consumer and its behavior on different settings, such as machine dynamics, cooling, and electronics. The obtained results reveal considerable potentials in energy saving and process efficiency.

This paper presents the developed measurement system architecture and related data acquisition as well as an analytical analysis approach. Moreover, an example of energy optimization measures will be described according to the applied analysis.

Introduction and Objective

"If you can not measure it, you can not improve it." - Lord Kelvin[1]

Energy is an issue in science, politics and several industrial sectors; up to now, it carries less importance in manufacturing [1]. Due to climate change and environmental reasons, stricter industrial requirements, especially automotive sector [2], costs and resource reasons in the context of green production as well as statutory requirements [3], energy efficiency has become a large research field.

The study of the BMWi [5] indicates that the industrial sector in Germany has a predominant share of 47% of the total energy consumption of all sectors. Going deeper into detail of the Life Cycle Assessment (LCA) of a machine tool, it can be seen that the use phase of a machine tool is the most relevant phase for energy consumption [6]. Awareness of energy consumption is seen as the basis for further analysis, and optimizations of the energy efficiency of a machine tool. It should also increase the awareness of consumption, provide

the grounds for energy efficiency improvements, and verify the improvements after implementation.
This paper introduces a developed multichannel measurement system which is designed to measure the energy consumption of machine tools with its specific energy forms such as electricity and compressed air, to implement and verify improvements.

State of the Art

A number of articles have been written on the clustering, optimization, and basic energy consumption in general. Results out of energy measurements are already published [6,7,8]. The results of these studies are hardly reproducible and/or comparable. The occurred data and results are strongly dependent on the measurement methodology and the used equipment. Up to now, there is no standard given and an obvious lack of definition of the measured system and the measuring conditions. Therefore, it is necessary to get a common and objective view on the data acquisition and measurement systems architecture and to define an energy audit [1,9]. An energy audit study should help an organization understand and analyze its energy utilization and identify areas where energy use can be reduced [10].

Up to now, there is no applied standard methodology, measurement device, or measurement requirement available that can manage the challenging requirements of en energy audit, e.g. the handling of specific energy forms of a tool machine [1] and ensuring a reproducible way of understanding the energy consumer behavior. As a part of the LCA [11], a potential basis for an onboard monitoring device as well as a possible statutory requirement [3] is necessary to take a closer look at the measurement system. From other more advanced industrial areas in energy saving, such as building technology, it is known that the knowledge of behavior of the consumer unit is the key point in energy efficient management [12].

System boundaries are necessary to define what kind of energy forms, energy consumptions, and losses must be considered within a machine tool energy assessment. According to the definition of machine tools [13], system boundaries include the automated production facility and, depending on the given features and machine functions, the peripheral equipment. Multi-used peripheral infrastructure, such as compressed air, should be proportionately considered. Measurements[2] [7] show that the peripheral equipment could have an extensive influence and must be kept in mind in an energy assessment.

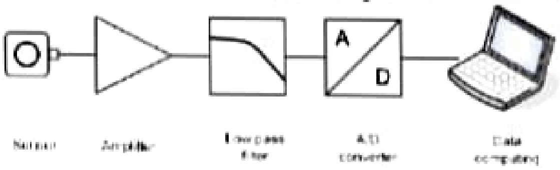
Electrical Consumer Measurement

The electrical active power measurement in three-phase current systems is based on the following general formula (Formula 1):

$$P_{eff} = U_{eff} \cdot I_{eff} \cdot \cos(\varphi) \qquad \text{Formula 1}$$

Due to the power network quality with the resulting asynchrony of each phase, it is needed to measure voltage U(t) and the current I(t) of each phase separately. The share of inductivity and capacitance of each electric consumer leads to an asymmetric dispersion of the phase-specific sinus waves and high range of cos φ. Harmonic waves have an influence on the Zero-Crossing-Detection within a measurement device and therefore on the identification of the periodic time T of the measured sinus waves [14]. This is a critical point in energy calculation.

Data acquisition with an n-fold sampling rate according to the signal of interest and the application of a Zero-Crossing-Detection filter can minimize the effects of harmonic waves.



$$f_{sample} \geq 2 \cdot f_{signal}$$ Formula 2

Fig. 1.Measuring chain setup

In the practical implementation (Fig.1), the measurements within the 50Hz network show that low pass filtering of 2000Hz fulfill the requirements of harmonic waves influence identification. The applied analog low-pass filters cut off all signals above 2000Hz. To avoid aliasing, the filtered signals of U(t) and I(t) are sampled by a sampling rate of 4000Hz by the A/D converter. This fulfills the Theorem of Shannon (Formula 2).

The signal can be acquired by a voltmeter for U(t) and by a hall effect sensor for I(t). Such devices are commercially available, can be used to reach the mentioned requirements [15]. The data acquisition and the Zero-Detection are combined in the measurement data computing within the measuring device.

The applied device offers pulse and analog output for signal acquisition and control reasons (Fig.2/Table1). With a refreshing rate of 0.2 sec of the computed effective power value, it guarantees a near-real-time data acquisition.

Table 1
Technical specification of a sample measuring device.

Measuring principle	3-phase direct voltage measurement with hall effect current transformer
Sampling rate	4000 Hz
Output sampling rate	max. 5 Hz
Measuring error	U,I ≤ ± 1,0 % of measuring range
Output signal	bidirectional serial interface RS232

Compressed Air Measurement

For compressed air, as well as other gases, two separate and independent sensors (Fig. 2) were installed: a calorimetric flow sensor and a pressure sensor based on a DMS ceramic sensor for monitoring reasons. Several technical units for compressed air can be utilized for measurements. The applied technical unit for compressed air usage is Nm^3 (standard cubic meter), according to DIN 1343[3]. In correspondence with the defined system boundary, the data acquisition is gathered independently from the compressed air generator. Compressed air is to be measured based on the following assumptions (Formula 3).

Assuming an adiabatic change of state:

$$P(t) = W(t) \cdot \dot{m}(t) = c_p \cdot T_1 \cdot \left[\left(\frac{p_1}{p_2} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right] \cdot \rho \cdot \dot{V}(t)$$ Formula 3

κ: isotropic exponent, 1.4
T_1: intake air temperature
p_1: intake pressure
p_2: outtake pressure
c_p: specific heat capacity
ρ: medium density

Simplified to $p(t) = p = const$, T_1, $c_p = const.$:

$$P(t) = c_p \cdot T_1 \cdot \left[\left(\frac{p(t)}{p_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right] \cdot \rho \cdot \dot{V}(t) = C_1 \cdot \dot{V}(t) \qquad \text{Formula 4}$$

The compression work within the compressed air system can be described by the adiabatic change of state. Assuming an ideal gas, the compression work can be calculated by the specific heat capacity, the intake air temperature, the in- and outtake pressure and mass flow.

Due to the uncertainties in the in- and outtake air temperature, humidity, thermodynamic behavior, and in- and outtake air pressure, the above-mentioned simplification is reasonable (Formula 4). The deviations within the air flow signal acquisition is assumed to be around +/- 10%. Taking the whole transformation path into account, +/- 30% inaccuracy is assumed on the computed output power.

The simplification leads to an infrastructural dependent transformation that is seen in figure C_1. Based on the defined system border with the focus on the machine, the common transformation figure in C_1 with the value of 6.5 – 7.5 kW/(m³/min)[4] for compressed air transformation is reasonable. Depending on the applied compressor and/or the compressed air distribution infrastructure, losses of up to 50% are possible[5]. The conversion factor C_1 represents a benchmark value in efficiency within the industry sector. The technical specification of the applied air flow measurement can be seen in Table 2.

Table 2
Technical specification of flow measurement.

Measuring principle	calorimetric flow sensor, according to DIN ISO 2533
Sampling rate	25 Hz
Temperature range	0...60 °C
Measuring error	3.5 % of measuring range under standard conditions DIN 1343
Max. throughput flow	150 Nm^3/h
Measurement category	According to Nm^3 / DIN ISO 2533

In combination the measurement system architecture can be seen in Fig. 2:

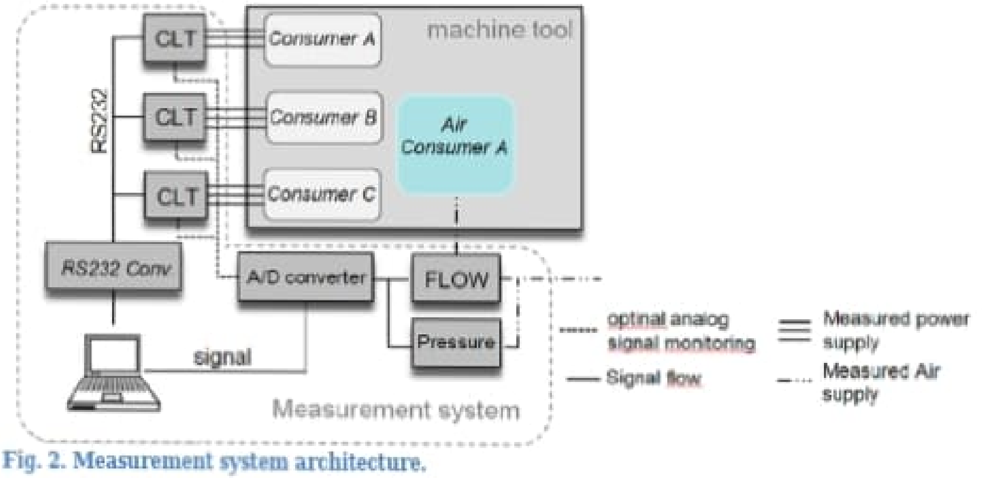


Fig. 2. Measurement system architecture.

Results and Conclusion

In a case study, a machine-specific reference process with known process parameters was measured (Fig. 3). A defined reference process can resolve typically used machine parameters as a reference measurement to correlate energy usage with the performed operations on the measured system. The resulting area chart in Fig. 3, on the basis of the measured individual process for the machine tool, is seen as a good reference assessment of a general machine tool. All measurements consist of the information of the machine state, effective power value of each consumer, and a referring time stamp.

As there is no methodological measurement standard for machine tools available, it is necessary to define common measurement start and end points and to distinguish between different machine states, such as emergency stop, ready for operation and machining cycle, within the measurement. The values are separated by color and initially ordered by their variance and then by their energetic importance (Fig. 3), which separates constant from variable loads.

The transformation of output power to energy consumption can lead to non-transparent statements if machine state independent measurements are taken under account. The measured power output is transformed into the energy share within the machine state – machining cycle – in Fig. 3.

Interpretation and Outlook

Simulations and optimization of machine tools cannot be made without reliable and reproductive measurement data. This measuring approach could provide reliable data for further actions. In this context, further methodological and technical standards must be developed to provide a transparent and reproductive energy measurement and energy assessment.

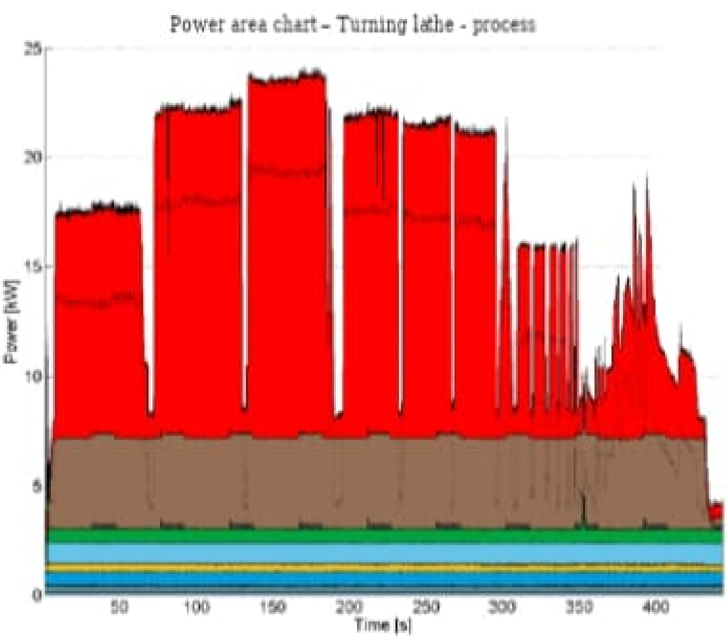


Fig. 3. Area chart of all measured consumers.

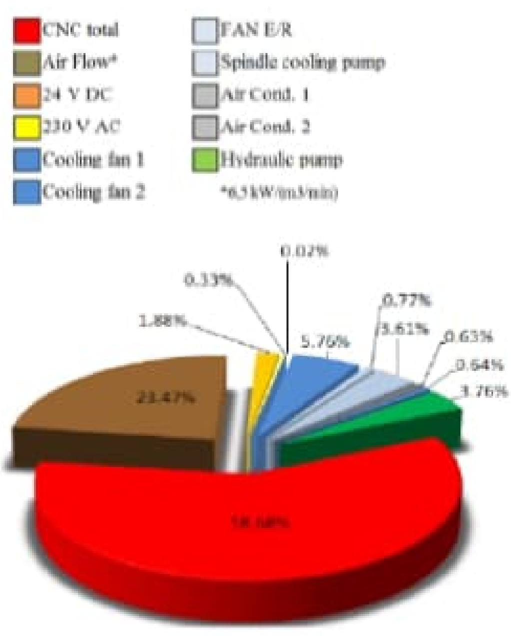


Fig. 4. Energy share of all measured consumers within the machining cycle time