The monitoring of transient regimes on machine tools based on speed, acceleration and active electric power absorbed by motors

M Horodinca
Department of Machine Tools and Tools, Machine Manufacturing Faculty, Technical University of Iasi, Romania, Bd. Dimitrie Mangeron, 61-63, 700050.
E-mail: horodinca@tuiasi.ro

Abstract. This paper intend to propose some new results related with computer aided monitoring of transient regimes on machine-tools based on the evolution of active electrical power absorbed by the electric motor used to drive the main kinematic chains and the evolution of rotational speed and acceleration of the main shaft. The active power is calculated in numerical format using the evolution of instantaneous voltage and current delivered by electrical power system to the electric motor. The rotational speed and acceleration of the main shaft are calculated based on the signal delivered by a sensor. Three real-time analogic signals are acquired with a very simple computer assisted setup which contains a voltage transformer, a current transformer, an AC generator as rotational speed sensor, a data acquisition system and a personal computer. The data processing and analysis was done using Matlab software. Some different transient regimes were investigated; several important conclusions related with the advantages of this monitoring technique were formulated. Many others features of the experimental setup are also available: to supervise the mechanical loading of machine-tools during cutting processes or for diagnosis of machine-tools condition by active electrical power signal analysis in frequency domain.

1. Introduction
Actually the use of active electrical power absorbed by the motor which supplies with mechanical power a machine tool is a common topic of scientific research, especially for control and monitoring [1]. Basically the motor is used also as loading sensor; the mechanical power required by machine tool is fully mirrored in the active electrical power. For the time being the evolution of the active electrical power (and sometimes the evolution of current [2]) presents many good opportunities for scientific research: cutting process monitoring [2, 3], tool wear [4] and tool breakage detection, power consumption optimisation related with unproductive times [5] and the condition of different components of machine tools [6], condition monitoring strategies on machine tool in order to reduce energy consumption [7], machine tools design for power consumption optimisation [8], etc.

However there are some unexploited resources of research, some of them related with the results presented in this paper. Mainly, the paper -in addition to the results previously published in [9]- claims and proves that some mechanical transient regimes in gearbox kinematic chains are well mirrored in the evolution of the electrical parameters of the energy absorbed by the motor (especially the active electrical power). A better understanding of transient regimes is given by the qualitative relationship...
between the active electrical power and the acceleration of rotation motion in the main kinematic chain as it is experimentally revealed here.

Generally speaking, the behaviour of any mechanical system electrically actuated is mirrored in the evolution of the energetic parameters of the actuator. Some research results on this topic were already published by the author [10, 11 and 12].

2. Experimental setup

In theory, an active electrical power sensor placed on the electrical power supply system of an AC motor (used to power a machine tool) and a computer assisted data acquisition system is a minimal setup useful for monitoring. The structure of this sensor proposed here below is more convenient.

According with figure 1 and [9], a simpler solution to replace the active power sensor is to use a voltage transformer (VT) that deliver the instantaneous voltage signal and a current transformer (CT) that deliver the instantaneous current signal, both placed on a phase of a three phase electric power supply system. Here we suppose that an AC electric motor is used to drive a lathe headstock gearbox (a Romanian lathe SNA 360). All considerations remain valid for a DC electric motor (which drives a CNC machine) if the transformers are placed before the AC-DC converter used to power the motor. The signals delivered by these two transformers (each one proportional with the voltage and the current respectively) are delivered to a data acquisition system (a numerical oscilloscope PicoScope 4424) and then -as numerical values- to a personal computer. Next, all relevant energetic parameters (e.g.: active electrical power, instantaneous electrical power, reactive electrical power, frequency, power factor, etc.) are calculated using appropriate computer programs written in Matlab.

In order to measure the rotational speed (or speed of revolution) a stepper motor is used as a speed sensor. The output shaft of the stepper motor is hold in a three-jaw chuck of the lathe main spindle. This sensor acts as an alternating voltage generator with the frequency and amplitude of signal strictly related by the rotational speed. The signal produced by speed sensor is delivered also to the data acquisition system and after that -in numerical format- to the personal computer.

3. Theoretical background

The theoretical considerations used for computer assisted calculus of active electrical power absorbed by the electric motor were presented in detail in [9]. Some considerations related with this calculus are also presented in [10, 11 and 12]. Using the numerical description of instantaneous voltage \( u[t_k] \) (delivered by the transformer VT) and current \( i[t_k] \) (delivered by the transformer CT) the numerical description of the active electrical power \( P[t_k] \) is given by the equation:

\[
P[t_k] \approx \frac{3 \cdot 2}{T} \sum_{k=s-\ell+1}^{s+\ell+1} (u[t_k] \cdot i[t_k]) \cdot \Delta t = \frac{3}{n} \sum_{k=s-\ell+1}^{s+\ell+1} (u[t_k] \cdot i[t_k])
\]  

(1)
Here \( s \) is the number of samples for \( u[t_k] \) and \( i[t_k] \) on half of a period \( T \) (with \( s\cdot\Delta t=T/2 \) and \( \Delta t \) the sampling period). Also \( T \) is the reciprocal of the instantaneous voltage frequency \( f \) (usually \( f=50 \text{ Hz} \)), \( l \) is the current number of samples for \( P[t_l] \), with \( t_l=l\cdot T/2 \). The sampling period of active electric power is \( T/2 \) (with a sampling rate \( 2\cdot f \), usually \( 100 \text{s}^{-1} \)). A multiplication factor equal with 3 is used because the AC motor is supplied with a three phase symmetrical electrical network.

There is a supplementary option (according with \([10]\)) to obtain the numerical description of active power: by low pass numerical filtering of the instantaneous electrical power \( p[t_k]=u[t_k] \cdot i[t_k] \).

The AC signal delivered by the rotational speed sensor contains 200 cycles per revolution. The current value of the time of semi-period \( T_i \) of AC sine wave (determined by computer with high accuracy) is involved in the calculus of the rotational speed of the main shaft \( n[t_i] \) as it follows:

\[
n[t_i] = \frac{l}{200 \cdot T_i} \text{ rev/s} \quad \text{with} \quad t_i = \sum_{j=0}^{i} T_j
\]

The angular speed \( \omega[t_i] \) is related by rotational speed by the equation:

\[
\omega[t_i] = 2 \cdot \pi \cdot n[t_i] = \frac{2 \cdot \pi}{200 \cdot T_i} \text{ rad/s}
\]

Let be \( m \) the number of samples for angular speed (\( i_{\text{max}}=m \)). For calculus of numerical values of the angular acceleration, the exact definition \( \varepsilon=d\omega/dt \) is approximated as \( \varepsilon=\Delta \omega/\Delta t_i \):

\[
\varepsilon[t_j] = \frac{\omega[t_{i+1}]-\omega[t_i]}{(t_{i+1}-t_i)} \text{ rad/s}^2 \quad \text{with} \quad t_j = \frac{(t_{i+1}+t_i)}{2}
\]

Here \( j=i, \) with \( j=1, 2, 3...m-1 \) and \( \Delta t_i =t_{i+1}-t_i \) is the sampling period.

The sampling rate of the rotational speed, angular speed and acceleration \((1/\Delta t_i)\) is variable, it has the value of \(200\cdot n[t_i] \text{ s}^{-1} \).

4. Experimental results and discussion

Figure 2 present a first result in computer assisted monitoring of a transient regime using simultaneously the evolutions of active electric power (curve I), angular speed (curve II) and acceleration (curve III). In order to have a comprehensive graphical description the magnitude of angular speed was increased 50 times and the magnitude of angular acceleration was increased 100 times.

Before the moment marked with A just a part of the kinematic chain of the lathe headstock gearbox is firmly coupled (the main spindle should theoretically be motionless). Practically because of internal residual friction inside an electromagnetic clutch (which is switched-off) the main shaft rotates slowly. In order to drive the gearbox in these conditions the electric motor absorbs 1200 W as active electric power. The main part of this power is converted in mechanical power and dissipated in the gearbox by mechanical friction as heating.

In A the electromagnetic clutch is switched-on; the main shaft starts to increase the rotational speed and the electric motor deliver to the gearbox more and more energy. Now the transient regime starts. It lasts until the installation on the level of stationary regime marked with D on figure 2 when the main spindle rotates with a constant rotational speed (17.43 rev/s or 1045.8 rpm), the angular acceleration is zero, and the absorbed active electrical power is constant (2750 W average value). It is important to remark that during this transient regime the angular speed (and rotational speed as well) doesn’t increase linearly. It increase quickly at the beginning (this is related with a first positive peak of 43.4
rad/s² on the angular acceleration evolution in B) and at the end (this is related with a second positive peak of 44.32 rad/s² on angular acceleration evolution in C). This type of evolution is caused by the temporary sliding inside the electromagnetic clutch and between belt and pulleys inside a flat driving belt transmission (this is placed between motor and gearbox).

It is very interesting to mention that the evolution of active electrical power absorbed during this transient regime is closely related by the evolution of angular acceleration, see the peaks B and C and the period between (the sliding begins in B and ends in C). The evolution of the acceleration completely explains the evolution of active power (also described before in [9] but without providing a consistent explanation). A part of the active power during transient regime is used (after conversion in mechanical power) for accumulation of kinetic energy in kinematic chain of the gearbox because during the transient regime a supplementary mechanical loading temporary occurs in the gearbox: the dynamic torque (the rotational inertia or the moment of inertia of kinematic chain multiplied with angular acceleration). This dynamic torque multiplied with the angular velocity defines a dynamic power delivered by motor and absorbed by the kinematic chain.

The angular acceleration has a major influence on the dynamic power. This dynamic power is quite high; therefore on figure 2 the active electrical power and angular acceleration has many similarities in transient regime. The dynamic power, angular speed and acceleration shown in figure 2 are useful to calculate the moment of inertia of the kinematic chain.

When the electromagnetic clutch is switched-off (in E) the active electrical power decreases at the level of 915 W. It doesn’t drops suddenly because of low pass numerical filtering. The rotation speed of the main shaft slowly decreases to zero (as it is expected, the angular acceleration is negative) the decoupled part of the kinematic chain uses the kinetic energy stored inside to supply the motion.

Figure 2 present some other transient regimes on the same lathe during an operating cycle described as follows:

- In A an electromagnetic clutch is switched-on in order to get a rotational speed of 532 rpm at the main shaft. As expected, as long as the speed increases there is a positive acceleration and a strong dynamic power with similar evolutions. We should mention that the acceleration evolution loses some details due to the numerical filtering.

![Figure 2](image-url)
- In B the rotational speed is constant (532 rpm), the acceleration and dynamic power are zero, the level of consumption of active electrical power is 1925 W. The gearbox runs in steady-state regime.

- In C the configuration of the kinematic chain is suddenly changed (using electromagnetic clutches) in order to increase the rotational speed from 532 to 831 rpm. There is a new transient regime well described in the evolutions of the dynamic power and acceleration. There is a peak of active power of 5625 W.

- In D the rotational speed is relatively constant. Now there is a second steady-state regime (no dynamic power, no acceleration). The electrical motor absorbs 2775 W (average value). However we should mention that according with figure 4 (which shows a detail on the evolution of active power and rotational speed in D area) the average value of power slowly decreases and the speed slowly increased. Because all the power is dissipated as heating in gearbox, the temperature of lubrication oil increases, so the viscous friction, mechanical loading and active power decreases. In consequence the rotational speed of the motor (and of the main shaft) increases (the speed of motor depends by mechanical loading, it has a negative slope).

- In E the configuration of the kinematic chain is changed again in order to reduce the rotational speed at 532 rpm.

![Figure 3](image.png)  
**Figure 3.** Some transient regimes during an operating cycle with different rotational speeds (the main shaft runs in idle regime).

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An interesting behaviour of the gearbox is highlighted here: the absorbed electric power drops temporary up to negative values. For a short time the kinematic chain works as a mechanical power supply (based on the kinetic energy stored inside). This power flows between the gearbox and the motor where is converted in active electric power and delivered to the electric power system. The motor works for a short time as a generator for electric power system and as a mechanical brake for the gearbox (on the motor output shaft the torque and the rotational speed have opposite directions). As in the case of transient regimes revealed in A and C, the evolution of angular acceleration is very similar with the evolution of active power.

- In F there is the same steady-state similar with those already described before in B.

- In G the electromagnetic clutch is switched-off, the mechanical power supply for the main part of the kinematic chain disappears, the active electrical power drops suddenly, the rotational speed decreases exponentially (this means that there is a dominant viscous friction in the kinematic chain), the motion of the main spindle is powered by the kinetic energy stored in the kinematic chain. As
expected, the angular acceleration is negative. The evolution of the rotational speed and angular acceleration here is useful to characterize the friction inside the kinematic chain.

Figure 4. A detail on the evolution of active power and rotational speed in D area from figure 3.

The negative power flow revealed in figure 3 is an interesting item in dynamics already discussed in [10, 11 and 12]. By electrical point of view, as an alternative at eq. (1), the active electrical power can be also numerical described [12] as it follows:

\[ P(t) = 3 \cdot U(t) \cdot I(t) \cdot \cos(\phi(t)) \]  

Here \( U(t) \) and \( I(t) \) are the RMS values of voltage and current on a single phase of the electrical supply network (these are systematically positive values) and \( \cos(\phi(t)) \) is the power factor (with \( \phi(t) \) the shift of phase between instantaneous voltage and current as harmonic signals). A negative electrical power can be explained only by a negative power factor. The transient regimes depicted in figure 3 can be also well described by the evolution of power factor as it is shown in figure 5. There are a few observations here:

1. There is a good similarity between the evolution of active electrical power and power factor. A variation of mechanical loading seems to be even better described by the evolution of power factor than the evolution of active electrical power. Unfortunately there is no a linear proportionality between mechanical power and the power factor.
2. The negative active electrical power occurs because the power factor is also negative (\( \phi(t) > 90^\circ \), here with a maximum value of 115.82 degrees for \( \cos(\phi(t)) = -0.436 \)).
3. It is confirmed here that a high mechanical loading applied to the motor means also a high power factor. A high power factor is advantageous from the point of view of electrical power supply system (it means a low reactive electrical power flowing between electrical power system and AC motor).

We should mention that the variation of the shift of phase is accompanied by the changing of frequency of instantaneous current (a future topic of experimental research).

The dynamic power occurs for any type of kinematic chain when the motion is accelerated. As an example, figure 6 present the evolution of the active electrical power absorbed by a DC motor which supply the kinematic chain of the main shaft of EMCO 55 CNC milling machine when the rotational speed is suddenly increases from 600 to 1200 rev/min. Due to the fact that the main kinematic chain is very simple, the steady-state consumption of active power is quite small.
5. Conclusions and future work

The main objective of this paper was to prove in experimental terms that there is a close relationship between the angular acceleration of the main shaft and the active electrical power absorbed by the driving motor during transient regimes on a machine tool. A computer assisted experimental setup was developed (a machine tool, sensors, computer aided data acquisition and processing) in order to generate with high accuracy the evolutions of active electrical power, rotational speed and angular acceleration, and collaterally some other results (e.g. the evolution of power factor). Some typical transient regimes on machine tools were depicted with several relevant results:

- the highlighting of dynamic mechanical power as a consequence of angular acceleration;
- the kinetic energy stored inside the kinematic chain due to the dynamic mechanical power was revealed;
- the description of a transient regime with negative mechanical power and active electrical power flow due to the elimination of a part of the available kinetic energy stored inside the gearbox;

![Figure 5. The evolution of power factor $\cos(\phi[t])$ during transient regimes depicted in figure 3.](image)

![Figure 6. The evolution of active power absorbed by the drive motor of EMCO 55 CNC milling machine during a transient regime.](image)
-the experimental demonstration that the active negative power flow is due to a negative power factor in electrical supply circuit of motor;
To conclude, the results presented in this paper contribute to a better understanding for the behaviour of the kinematic chain during transient regimes.
The experimental setup will be used later on for some new purposes in experimental research such as:
- active power signal analysis in frequency domain with identification of variable components and the relationship with the behaviour of gearbox parts;
- computer assisted detection of the torsional modes of vibration in kinematic chains;
- cutting processes and tools condition monitoring based on the evolution of active electrical power delivered to the kinematic chain;
- increasing the stability of cutting processes on machine tools (against machining vibrations) using negative mechanical power flows (generated with electrical actuators placed in the proximity of the cutting tool or workpiece);
A privileged research topic will be the optimisation of kinematic chains structure and machine tool exploitation. Some considerations exposed here are available also for any other electrically actuated mechanical system.

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