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VALIDATION OF A POWER MEASUREMENT SYSTEM IN THE MILLING PROCESS USING HALL SENSORS

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Abstract. *In machining, the power consumption is a useful output parameter to study the machinability of materials, the performance of cutting tools and cutting fluids and to diagnose the conditions of the cut. It can be obtained from measurements of the effective electric power of the motor that rotates the main shaft of the machine tool. The objective of the present work is to build and validate a measurement system of the electric power of a CNC machining center during the milling process. The system consists of Hall sensors that obtain data from the electrical input lines that feed the main motor of the machine and the signal generated is amplified and converted into digital information to be processed computationally. For validation of the results obtained by the power measurement system, a rotating dynamometer was used to measure the machining forces, allowing the calculation of the cutting power for comparisons. The difference of the machining power measured by the two systems was about 5%.*

Keywords: *Milling process, Power measurement system, Hall sensors, Machining forces.*

1. INTRODUCTION

Milling is a machining operation that consists, in most cases, of the simultaneous longitudinal or transversal feed movements of the workpiece, attached to the worktable, and the rotation of the tool (Machado et al., 2015). One important variable related to the milling processes is the effective machining power (Trent; Wright, 2000), that is the sum of all the powers involved in the machining process (cutting and feed). However, because the cutting speed is much higher than the feed speed the feed power can be negligible and the machining power can be fairly calculated considering only the cutting power. The cutting power can be calculated by the Eq. (1) and Eq. (2). The motor of the machining shaft is responsible for most of the energy required during the cutting process, so, evaluate the machining power by the active electric power is widely acceptable (Machado et al., 2015).

$$P_c = \frac{F_c v_c}{60\eta}\ (W) \tag{1}$$

$$P_c = \frac{a_p v_c f k_c}{60\eta}\ (W) \tag{2}$$

Where:

P_c (W) = Cutting power;
F_c (N) = Cutting force;
v_c (m/min) = Cutting speed;
η = Machine efficiency;
f = Feed per Revolution;
K_c (MPa) = Specific Cutting Pressure;

The power measurement system proposed in this work was conceived using an indirect monitoring method, which aims at measuring the variation of the electric current and voltage so that, through mathematical manipulations, the active power of the process is obtained. The monitoring device is divided into two parts: one dedicated to the measurement of the electric current and another to the measurement of the electric voltage. Both parts follow the same logic of information management flow, the only differentiating factor being the voltage and current transducers themselves.

The current transducer is made up of semiconductor elements, allowing magnetic sensing by Hall Effect. This is possible by the presence of a magnetic field perpendicular to the flow of electric current on the semiconductor material, a principle that allows the generation of an electric voltage. Such a voltage is called Hall Voltage and is proportional to the flux density and the electric current. Hall effect voltage transducers are based on the same principles as electric current transducers. This Hall Effect voltage transducer is constituted by the assembly of an electric current transducer in series with a primary electrical resistance. Thus, the voltage is measured by the passage of a current proportional to the same resistor (Ramsden, 2001).

The minimum requirements for this monitoring system are: a computer; electric current and voltage sensors with Hall effect operation, these being of high frequency to ensure accuracy and ease acquisition of the signals, operational signal amplifiers and an analog / digital (A/D) data converter. In this work were used a current transducer model HAS 50-S, a voltage transducer model LV 20-P, both shown in Fig. 1. A digital amplifier (741 series) and a NI USB-6221 data acquisition board were also used with an acquisition rate of 10 Khz.

Figure 1. Current and voltage sensors, respectively.

For the developed power system, amplification, attenuation and isolation of the signal were required. This system is composed of two circuits, one for voltage and one for current, with operational amplifiers that together with resistors, allow the output signal of the voltage sensors to have a constant gain. Using the Eq. (3), the conditioned signal is obtained.

$$Vo = A.V_i \tag{3}$$

Where:

V_0 (V) = Conditioned signal;
V_i (V) = Sensor output signal;
A (A) = Current gain;

Figure 2a shows the signal conditioning circuit of the voltage sensor and Fig. 2b a photo of the implemented circuit. The inverting amplifier seen in this figure is the same one used for the signal of the current sensor, whose characteristic equation is equal to Eq. (3), with the output signal inverted.

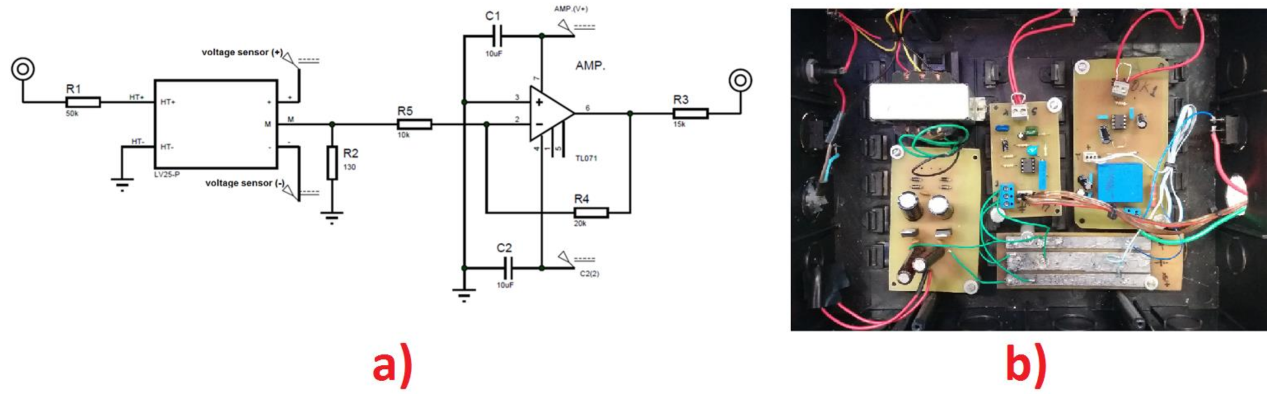

Figure 2. Voltage sensor in conjunction with the conditioning circuit. (a) Schematic drawing. (b) Circuit assembled.

The cutting power can then be estimated from the product of the average active electric power given by the Eq. (4) and the spindle efficiency calculated by the Eq. (5) (Alexander; Sadiku, 2013).

$$\mathrm{P} = \frac{1}{T}\int_0^T p(t)\, dt \quad (4)$$

$$p(t) = i(t).v(t) \quad (5)$$

Where:

P (W) = Average electrical power;
T (s) = Period of time of the signal;
$p(t)$ (W) = Instantaneous electric power;
$i(t)$ (A) = Instantaneous electric current;
$v(t)$ (V) = Instantaneous electric voltage;

The signals obtained by the sensor can be expressed in the form of an infinite sum of the sine and cosine functions of the integral multiples of the fundamental frequency of the electric lines, in this case 60Hz, thus characterizing the Fourier theorem (Alexander e Sadiku, 2013). For this reason, the average power of a phase can be defined by Eq. (6):

$$P_f = P_{dc} + \sum_{n=1}^{\infty} P_n \quad (6)$$

Where:

P_f (W) = Average power of a phase;
P_{dc} (s) = Constant component of the Fourier series of the mean power of the phase;
P_n (W) = Harmonic components of the Fourier series of the mean power of the phase;

Considering the previous equation, we obtain that the total average power is the sum of the average powers in each voltage and electric current related harmonically, that is, the value of p (t) of Eq. (5) will only be different from zero when there is the product of a harmonic component of voltage and current of the same order. Therefore, the average of the total instantaneous power obtained by Eq. (4) will result in the average power required for the calculation of the cutting power, even with the presence of harmonic distortion.

Since the induction electric motors are manufactured in order to have balanced three-phase windings, that is, the coils that make up their stator have equal impedances (Del Toro, 1994), the average powers developed in each phase will be the same and, for this reason, the power can be given by Eq. (7):

$$P_t = 3.Pf \quad (7)$$

Where:

P_t (W) = Total cutting power;

2. EXPERIMENTAL PROCEDURE

Dry-milling tests were performed using uncoated High Speed Steel (HSS) milling cutters manufactured by OSG Sulamericana Ltda, model D327 EDS 801/1, with 10 mm of diameter and four cutting edges (Fig. 3). The workpiece material was made from FC350 pearlitic gray cast iron, with refined graphite and addition of molybdenum, supplied by the TUPY S.A. The microstructure of the specimen is illustrated in Fig. 4. The milling cutters were replaced by a new ones every time the flank wear reached 0.1 mm in one of the tooth.

Figure 3. Example of the one of the cutters used during the tests.

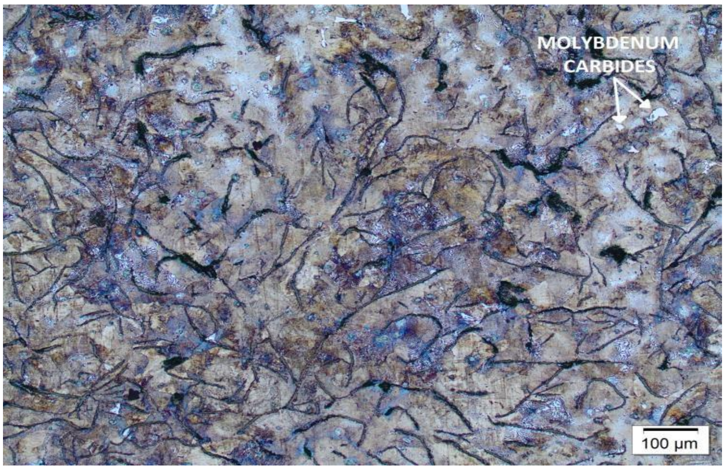

Figure 4. Microstructure of the workpiece - FC 350 gray cast iron. Etched with Nital 2% for 30 seconds.

The tests consisted of machining channels in the workpiece with a width equal to the milling cutter diameter (slot milling), which were performed in the ROMI Discovery 760 CNC machining center. The machining forces were measured using a rotating dynamometer model 9123C, and signal amplifier model 5223, both manufactured by Kistler. The cutting conditions used are listed below, with 3 replicates per condition, for a total of 36 tests. The tests were sequenced according to Tab. 1.

- Tool overhang length = 40 mm;
- *ae* = 10 mm;
- *ap* = 0.5, 1 e 2 mm;
- *fz* = 0.1 and 0.2 mm/tooth;
- *vc* = 10 and 20 m/min;
- *Lf* = 30 mm

Table 1. Sequence of tests performed in this work.

	ap (mm)	v*f* (mm/rev)	*vc* (m/min)
1	0.5	0.10	10.0
2	1.0	0.10	10.0
3	2.0	0.10	10.0
4	0.5	0.20	10.0
5	1.0	0.20	10.0
6	2.0	0.20	10.0
7	0.5	0.10	20.0
8	1.0	0.10	20.0
9	2.0	0.10	20.0
10	0.5	0.20	20.0
11	1.0	0.20	20.0
12	2.0	0.20	20.0

3. RESULTS AND DISCUSSIONS

Figure 4 shows the cutting power given by Eq. (1), after measuring the force with the dynamometer and the cutting power given by Eq. (7) after measuring the current and voltage by the Hall sensors. Those values where compared with the theoretical cutting power given by the Eq. (2), being used in the calculations the parameters of a hardened cast iron with Kc of 3000 and 2700 MPa for the feeds of 0.1 and 0.2 mm/rev respectively (Carbide Catalogue Cb005, 2001). A good agreement was observed between the values of the three powers, especially those measured by the dynamometer and the Hall sensor, where all the measurements were within the respective standard deviations. It is observed, however, that the tests 3, 5, 6 and 12 presented values of real power superior to the theoretical one. This can be explained by the fact that these conditions are the most severe in relation to the power required for the machining and, with the increase of the machining forces, factors such as vibrations and rigidity of the machining center, not foreseen in the theoretical equation, have a bigger influence on the cutting power, so that the actual value is higher than the theoretical one.

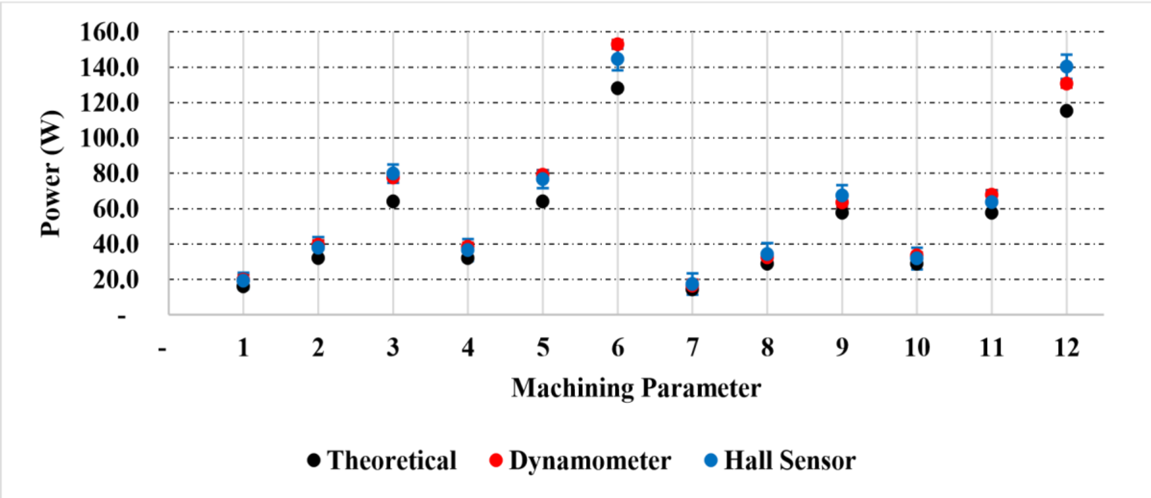

Figure 4. Results of the cutting power.

Figure 5 shows the variation (in percentage) of the power determined by the different systems investigated in this paper. For all the cases the measurements obtained by the Hall sensor and the dynamometer were statistically similar. It can also be inferred that the Hall sensor presents a greater inaccuracy of measurement in relation to the dynamometer, since it showed an average standard deviation of 5.9%, against 2.5% by the dynamometer. This is due to the fact that the dynamometer performs direct measurements of the system, whereas the hall sensor because it is based on indirect measurements is more subject to fluctuations of the electric network. The mean percentage difference of the hall sensor measurements in relation to the dynamometer was about 5%, which illustrates the good resolution of this system especially when considering its low cost in relation to the dynamometer.

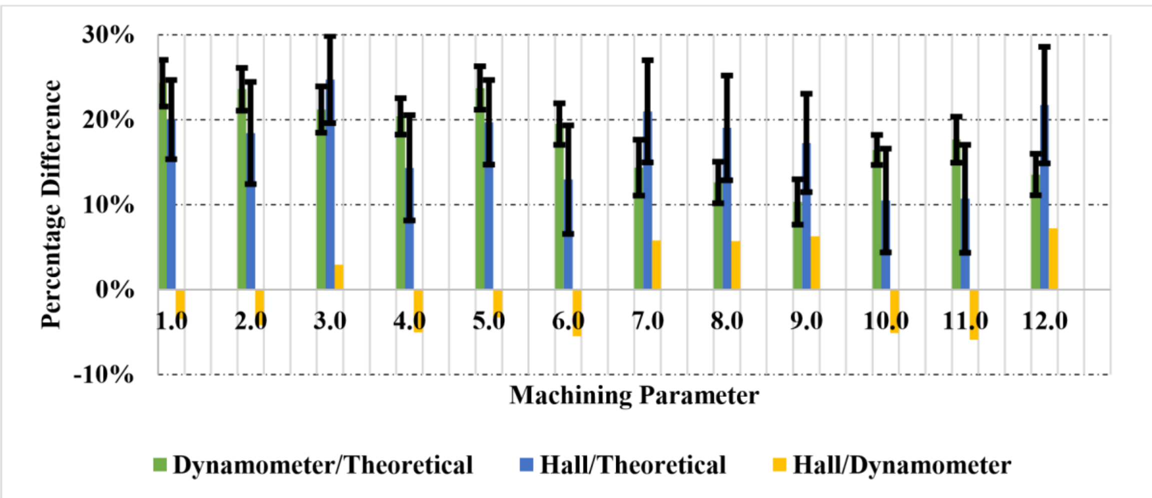

Figure 5. Percentage difference between the power evaluation systems.

4. CONCLUSIONS

The machining power in slot milling of FC 350 gray cast iron evaluated through the use of hall sensors presented a good agreement with the theoretical values and with the values calculated after measurements of the cutting force by a rotating dynamometer. As expected, due to the fact that it is an indirect measurement, the Hall sensor power measurement showed a slightly greater dispersion in the results than using the dynamometer. However, the Hall sensor system is much cheaper that the dynamometer system. Finally, it was observed in some tests that the theoretical values of the machining power distanced from the real ones as the machining forces increased, since factors such as rigidity of the equipment, not considered in the adopted equations, became more relevant.

5. ACKNOWLEDGEMENTS

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