Energy Management of Cordless Hand Tools

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The paper presents the results of the energy management investigations of the PSR 200 LI cordless screwdriver (Figure 1) carried out as part of the research work performed for Robert Bosch Power Tool Kft. (Miskolc).

Key words: energy management, Robert Bosch Department of Mechatronics

1 Introduction

The Robert Bosch Department of Mechatronics was established at the University of Miskolc with support from the Bosch companies in Hungary on 1 June 2005.

The objective of the cooperation between the Bosch companies in Hungary and the University of Miskolc is: *the application and widening of engineering and scientific knowledge in the research into, training in and application of mechatronics as well as ensuring practice-oriented training and meeting the demand of the factories for engineers.*

The establishment, equipment as well as the operation for three years of the Department and the laboratories were to the greater extent financed by the Bosch companies established in the region of Eastern Hungary such as Robert Bosch Elektronika Kft. (Hatvan), Robert Bosch Power Tool Kft. (Miskolc), Robert Bosch Energy and Body Systems Kft. (Miskolc) and Bosch Rexroth Pneumatika Kft. (Eger), and to a smaller extent by Deutscher Stifterverband für die Deutsche Wissenschaft.

The support covers the invitation of visiting professors, their involvement in academic activities, teaching material development and adoption of teaching materials, and cooperation in joint projects, which are to be completed in collaboration with the University of Duisburg-Essen.

After three years, from 1 July 2008 on, the University of Miskolc takes over the operation of the Department, with the relations of the Department with the Bosch companies continuing to play a major role in its life.

One of the priority tasks of the Department is to perform research and development work on commission for companies in the region involved in mechatronics, primarily for Bosch factories. The income generated in this way provides the foundations for the day-to-day activities of the Department for three years. The R&D contracts entered into with the different factories are of uniform structure and meeting the legal requirements. The research work done is of highly varied character in accordance with the factory profiles. The following presents one of the projects.

2 Energy management investigations of PSR 200 LI cordless screwdriver

It is a general endeavour of development engineers that machines and devices should offer high-standard services, i.e. they should carry innovative solutions, should be more and more intelligent and have favourable energy consumption. Meeting the requirements takes place in an environment of the given technical and economic possibilities and considerable competition. In order to achieve the above aim, leading companies have elaborated mechatronic solutions that are characterised more and more by spatial and functional integrationAdditional services involve additional energy consumption and are reflected in the prices of the machines. For the buyers it is only worth it if they find the price proportional to the services offered by the product.

The paper presents the results of the energy management investigations of the PSR 200 LI cordless screwdriver (Figure 1) carried out as part of the research work performed for Robert Bosch Power Tool Kft. (Miskolc).

Bosch is a market leader also in cordless DIY tools. The company developed the first Li-Ion technology cordless screwdriver, IXO, in the world, which is the most successful product of the company thanks to its sales in the order of million items. The example of IXO has shown that there continues to be a demand for innovative products even in tough competition. Bosch has set the objective to be the first to market products with new lithium batteries in the various performance categories, thus preceding the competitors. IXO was followed by the 10.8V PSR 300 Li and the 7.2V PSR 200 Li.

The tool was developed by Hungarian engineers with support from German colleagues. The innovative properties of the tool are as follows, e.g.:

- favourable performance/mass, and performance/volume ratios,
- Lithium-Ion technology, having the advantages of e.g. maintaining the charging level for a long time and chargability without time restrictions, and
- electronic moment control.

The objective of the investigations is: quantitative determination of the critical places causing losses in the kinematic chain of the PSR 200 LI cordless screwdriver, quantitative determination of the losses, and preparation of proposals for improving efficiency, e.g. in a modified construction or in the current structure.

Figure 1. PSR 200 LI cordless screwdriver

A. Efficiency

One important parameter characterising the quality of the electrical hand tool is the ratio between the useful energy used for work and the input energy to the machine. This relationship is expressed by efficiency:

$$\eta = E_u / E_{in}, \tag{1}$$

where:

- E_u is useful energy,
- E_{in} is input energy.

All manufacturers have the aim that the efficiency of the practical machine should be as close to 1 as possible, that is as small a part of the input energy should be lost as possible. The objective of energy management investigations is to explore the losses quantitatively and possibly to reduce and minimise them.
Examination methods: efficiency analysis and the methodical exploration of the factors influencing efficiency were performed by the combined application of theoretical computation and experimental measurement methods.

2.1. Energy management investigations

The kinematic change of the PSR 200 LI cordless screwdriver is shown in Figure 2, where the electric motor as an energy converter (electrical energy – mechanical energy) has a predominant role. The total efficiency of the screwdriver is given by the product of the efficiencies (2) of the part units as shown in Figure 2 with the notations following from Figure 2.

$$\eta_{total} = \eta_{el} \times \eta_{mech} = \eta_{bat} \times \eta_{cont} \times \eta_{elmot} \times \eta_{mech} \qquad (2)$$

Cordless Screwdriver		
Electrical drive		***Mechanical drive***
Battery	*Control circuitry*	*Mechanic kinematic chain*

Electric motor

Figure 2. Kinematic scheme of the PSR 200 LI cordless screwdriver

2.1.1. Losses of the main electrical circuit (efficiency)

The losses of the primary electric circuit were determined *by measurements* on a replacement connection. In the primary electric circuit regarded as a series circuit the measurements were performed in both senses of rotation. The power consumption of the control circuit, and thus its losses, were regarded as negligible compared with the primary circuit. In the course of the measurements operational conditions were created, and simultaneous measurements were performed at every point at the same time in order to ensure the constancy of the battery voltage. The simultaneous measurements were repeated three times, with the batteries charged prior to the measurements. The devices used for the measurements are 2 Spieder 8, a force transducer, a 1000 N Hottinger force transducer cell, and a purpose-made torsion spring loading device.
The tests carried out are as follows:

- No-load run with left-hand and right-hand sense of rotation at ambient temperature (22 °C),
- No-load run with left-hand and right-hand sense of rotation at 50 °C,
- No-load run with left-hand and right-hand sense of rotation without epicyclic gear,
- measurements under load with right-hand sense of rotation.

Measurements under load were carried out in the various load stages (stages of moment 1-6) of the tool only for right-hand rotation, with artificial load, since the no-load measurements showed only negligible differences between the two senses of rotation. Figure 3 shows the layout for the measurements under load, and Figure 4 shows the parameters recorded for stage of moment 4 (U_m – motor voltage, U_a – battery voltage, M_o- moment on the motor).

Figure 3.
Measurement bench layout for measurements under load

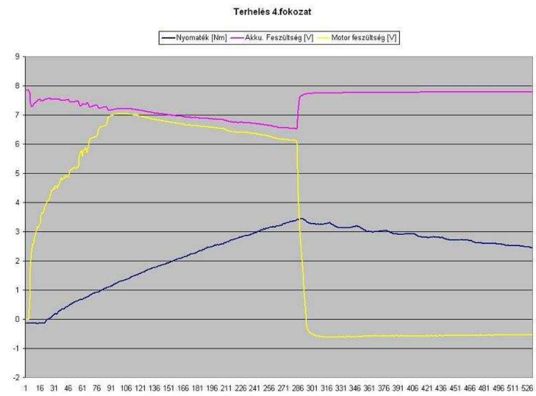

Figure 4.
Changes in measurement parameters in load stage 4

On the basis of the measurements and calculations the total efficiency of the tool, the electrical efficiency and separately the efficiency of the electric motor were determined, with their curves shown in Figure 6. Mechanical efficiency was obtained from the measurement results.
The efficiency of the electric motor was also determined theoretically and the results showed a good agreement with the data given by the manufacturer. The relationship expressing the efficiency of the motor (η_{elmot}) is (3):

$$\eta_{elmot}(M_0) = \frac{P_{out}(M_0)}{P_{in}(M_0)} = \frac{\frac{M_0}{k}\left(U_0 - \frac{RM_0}{c}\right)}{\frac{M_0}{k}\left(U_0 - \frac{RM_0}{c}\right) + \frac{RM_0^2}{c^2} + \frac{M_{fr}}{k}\left(U_0 - \frac{RM_0}{c}\right)}, \quad (3)$$

where the parameters are as follows:

1) *c:* motor constant
2) *R:* resistance of the rotor winding (ohm)
3) *k:* constant depending on the motor assembly
4) U_0: output voltage (V) of the DC motor
5) P_{out}: delivered power (watt)
6) M_{fr}: moment of friction on the shaft of the motor (Nm)
7) P_{in}: input power (watt)
8) M_0: moment on the motor (Nm)

2.1.2. Mechanical losses, losses of the epicyclic gear (efficiency)

Determining the mechanical losses, the losses of the epicyclic gear (efficiency) theoretically makes a comparison possible with the values of mechanical efficiency resulting from the measurements. In determining mechanical losses the ventilation losses were also taken into account. The function of the three-stage epicyclic gear used in the tool is to reduce the revolution number of the motor to the necessary technological revolution number and to increase the moment. Figure 5 shows the kinematic scheme of series-connected, identical k+b type epicyclic gears.

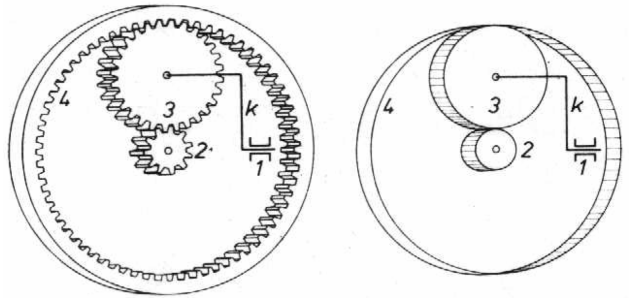

Figure 5. Kinematic scheme of k+b type epicyclic gear

Without going into details of the calculations, the efficiency (η_I) of a single epicyclic gear stage is expressed by equation (4):

$$\eta_I = 1 - \left[6\mu \left(\frac{1}{z_1} + \frac{1}{z_2} + \frac{z_1}{z_2} \left(\frac{1}{z_2} - \frac{1}{z_3} \right) \right) + \frac{2\mu d_{cs}}{m \cos \alpha_0} \frac{(z_1 + z_2)}{z_2 (2z_1 + z_2)} \right]. \tag{4}$$

The efficiency of the three epicyclic gears ($\eta_ö$), including the axial load on the drive, is described by equation (5).

$$\eta_{total,mech}(M_{in}) = \frac{M_{in}\eta_I^3 - \frac{\mu_{ax}F_{ax}}{3}\left(D + \frac{d^2}{D+d}\right)\left(\frac{z_1}{2(z_1+z_2)}\right)^3}{M_{in}} \tag{5}$$

Notations in the above equations are:

• μ: sliding friction factor of the contact surfaces	• μ_{ax}: friction factor of axial pin
• z_1, z_2, z_3: number of teeth of sun wheel, epicycloidal wheel and ring wheel, respectively	• F_{ax}: axial, technological force (N)
• d_{cs}: pin diameter (mm)	• *D, d:* big and small diameter of the contact annular surface of the shaft (mm)
• *m:* gear module (mm)	• M_{in}: driving moment (Nm)

Equation (5) can be written in the general form of equation (6):

$$\eta_{total,mech}(M_{in}) = A - \frac{B}{M_{in}}, \tag{6}$$

where factors A and B depend exclusively on the geometrical parameters of the drive, the friction conditions and the axial technological force. Including torque moment (M_{ki}) in the equation, gives :

$$\eta_{total,mech}(M_{out}) = \frac{AkM_{out}}{B + kM_{out}} = \frac{0{,}01M_{out}}{0{,}0022 + 0{,}011M_{out}}. \tag{7}$$

The efficiency values revealed and the tendency in their change versus moment of load is shown by Figure 6. The efficiency curve η_{total} shows the least advantageous limit, the working efficiency of the tool is more favourable than that.

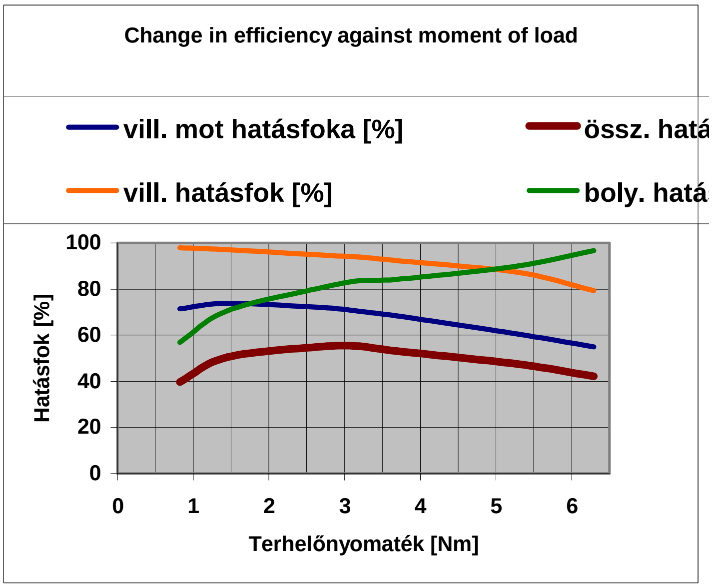

Figure 6. Efficiency curve of PSR 200 LI cordless screwdriver

2.1.3. Factors influencing the efficiency of the epicyclic gear and the kihajtó tengely

Examining equation (6) in detail, it can be stated that an increase in ***A*** and/or a reduction in ***B*** makes it possible to increase the efficiency of the epicyclic gear.

*Factor **A** can be increased in the following ways*:

- increasing the teeth module,
- and/or reducing the diameters of the pins on the carrier,
- and/or reducing the friction factor within the epicyclic gear.

Without going into the details of the results, it was stated that it was the change in the friction factor that can exert the most significant influence on mechanical efficiency (Figure 7): e.g. a change of the value a μ=0.01 exerts a 3% influence on the efficiency of the epicyclic gear.

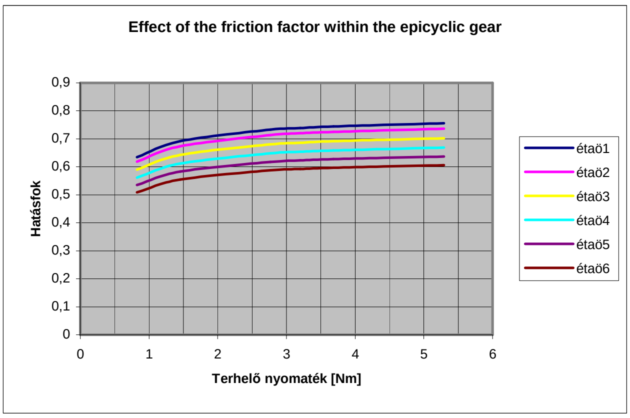

Figure 7. Effect of the friction factor of value of the epicyclic gear on efficiency

2.1.4. Reducing factor B can be achieved in the following ways:

- reducing the friction factor arising at the axial support of the tool holder pin,
- reducing the technology force.

On the basis of examining the above in the actual range it was found that none of the parameters exerted a considerable influence on a significant improvement in the efficiency.

3 Conclusion

In cordless screwdrivers, the modular construction according to the loading parameters and the design aiming at the optimum working range ensure that they work in the most favourable efficiency range. The starting points for the design are determined by the technological requirements and the market demand. The favourable solution in terms of energy management is achieved by the iterative selection of the electrical motor driving the tool and the drive, taking into account the principle of modular construction according to the parameters. The cordless screwdrivers of the Robert Bosch Power Tool Kft. meet the requirements of the design described above and rank among the top in their category in terms of the number of screws that can be driven with one charge.
In terms of mechanical efficiency, it is of great importance that the uniform quality of the epicyclic gears and their appropriate friction factor (lubrication) in ensured.
The electrical losses in the primary circuit naturally increase in the upper range of moment. In contrast, mechanical losses show a decreasing tendency with increasing moment due to the reduction in the number of revolutions.

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References

[1] BOSC-MOST: *a Bosch csoport miskolci gyárának lapja*, 2005. szeptember, II. évfolyam 3. szám
[2] Ten Bosch: Gépelemek
[3] Terplán Z.: *Fogaskerék-bolygóművek*, Műszaki Könyvkiadó, Budapest, 1976
[4] Johnson Electric Industrial Manufactory LTD: *Out Nominal Motor Curves*
[5] Robert Bosch Mechatronikai Tanszék: *A PSR 200 LI akkumulátoros csavarozógépek energiamenedzsment vizsgálata*, Kutatási jelentések (2006- 2007.) Projektfelelős: Patkó, Gy., Témafelelős: Jakab, E., Kidolgozók: Jakab, E., Szilágyi, A., Tatár, S., Csukás, G., Bihari,