RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Mechanical Engineering
Institute of Mechanical Engineering Technologies

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THE OPTIMIZATION OF THE AUTOMATED ASSEMBLY PROCESS OF FIXED THREADED JOINTS

Department: Mechanical Engineering

Sub-department: Mechanical Engineering Technology

Summary of doctoral thesis

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APPROVAL

I approve that I have developed this doctoral thesis that is submitted to Riga Technical University for gaining doctoral degree in engineering. The doctoral thesis is not submitted to any other university for gaining academic degree.

Ivans Grinevich …………………………….(Paraksts)

Date: ………………………

The doctoral thesis is written in Latvian language, contains an introduction, 7 chapters, conclusions, bibliography, 37 figures, 20 tables, 72 pages. The bibliography contains 31 sources.

CONTENT

OVERALL CHARACTERIZATION OF THE DOCTORAL THESIS

Actuality of the theme

In the doctoral thesis “The optimization of the automated assembly processes of fixed threaded joints” the nut driver’s electric power consumption studies depending on the corresponding fixed threaded joint’s assembly time are made. So far there are no recommendations from the tool manufacturers for nut driver’s optimal operating modes (the conclusion is made based on the attached instructions which provide instrument manufacturers), when evaluating this aspect taking into account the electrical power consumption and assembly time for different types of fixed threaded joints (wood, metal, plastic, etc.) and also taking into account obtainable tightening moments. In the examined literature sources [3,4,5,6,7,8] which deal with the opportunities concerning the optimization of the automated assembly processes of fixed threaded joints, not enough attention is paid to the reduction of the instrument’s energy consumption which is one of the main tasks in the industrial process because it directly impacts production costs.

Aim and objectives of the doctoral thesis

The aim of the doctoral thesis is to optimize the energy consumption according to assembly time for fixed threaded joints in automated assembly. To reach the aim following objectives were proposed:

1) To examine screwdriver’s usage instructions.
2) To calculate the tightening torque for the selected bolts.
3) To determine theoretically the consumption of electric power and assembly time for selected bolts.
4) To prepare the experimental equipment with a measuring complex that is intended for research.
5) To determine practically the electric power consumption and the assembly time for selected bolts.
6) To make processing and comparative analysis of the obtained results.
7) To examine additional ways how to reduce electric power.

Research methodology

For the solution of the main task - the optimization of the nut driver’s electric power consumption depending on the corresponding fixed threaded joint’s assembly time, the following research methods were used:

1) To state the assembly time for the threaded joint a computer program 'Sony Sound Forge Audio Studio 10' was used.
2) To create the electronic tables and make calculations Microsoft Excel software was used.
3) Tightening torque was determined by unscrewing torque.
4) Energy consumption was determined using USB oscilloscope (Picoscope 2205).

Scientific novelty and main research results

Scientific novelty and the main results are:

1) It was stated that nut driver - screwdriver has such modes of operation, at which it is possible to optimize energy consumption depending on the assembly time.

2) It is estimated that the theoretical calculation is more labour-intensive and less accurate, that's why optimizing the energy consumption it is more efficient to make practical measurements.

3) It was found the option for additional energy reduction making fixed threaded joint's assembly by switching off the power at the moment when the set torque is reached.

4) The experimental device with a measuring complex was prepared for the research performance.

5) How an innovation could be mentioned such fact that for the speed measurement and time estimation a computer sound card was used.

All of the above mentioned results are a new contribution to the scientific engineering technology.

Practical application

Studies carried out in the given doctoral thesis "The optimization of the automated assembly processes of fixed threaded joints", allow to determine the percentage of the reduction of electric power consumption of the given nut driver and to add the power-saving schemes to instrument manufacturers' usage manuals. The calculations show that it is possible to find nut driver's optimal mode of operation in order to prolong its lifetime, reduce electric power consumption and improve the quality of threaded joint.

The author defends this work

1) The calculation method for nut driver's optimal operation mode determination (as an optimization criterion is chosen nut driver's power consumption).
2) Equipment's consumable energy reduction opportunities when using it effectively.
3) The experimental equipment for the studies of fixed threaded joint's automated assembly process.

Approbation of the doctoral thesis

For the main results of the doctoral thesis several reports are given in the following conferences receiving appreciative evaluation:

<u>In Latvia:</u>

- Mozga N., Grinevichs I., Kandis J., Brensons I. Research of Influence of the Form of Details on Accuracy of Assemblage // RTU zinātniskie raksti. 6. sēr., Mašīnzinātne un transports. - 31. sēj., 2009.g., 67.-70. lpp.
- Griņevičs I. Mehānisko elementu salikšanas īpatnības mašīnbūvē. Seminārs „Mašīnzinātnes sasniegumi nanotehnoloģijās", 29.09.2011. Latvija, Rīga.

<u>Abroad:</u>

- Natalija Mozga, Ivans Grinevichs. Features of the scheme of basing on rotating rollers at automatic assembly of the thread connections, 12th International Research/Expert Conference, 26.08.2008.-30.08.2008. Istambul.- Turkey, 349.-352.pp.
- Natalija Mozga, Francis Sudnieks, Ivans Grinevichs. Quality assurance of performance of automatic assembly operations on rotors, 53.IWK Internationales Wissenschaftliches

Kolloquium, 08.09.2008.-12.09.2008. Vācija, Ilmenau.-Ilmenau, IlmPrint GmbH Digitales Druckzentrum Langewiesen, 331.-332.pp.

- Mozga N., Grinevichs I. METHODS USED FOR THE THREADED JOINT'S FORCE CONTROL // 7th International Conference of DAAAM Baltic "INDUSTRIAL ENGINEERING", 22.-24. April, Tallinn, Estonia, 2010, 96-100.pp.
- Grinevichs I., Mozga N., Springis G. The providing of ultra precision conditions for details' pressing processes on rotary machines // ECCM 14. 14 th European Conference on Composite Materials, Hungary, Budapest, 7.-10. June, 2010, pp. 5, CD proceedings.
- N.Mozga, I.Grinevichs, "Research of automatic assembly of details on the rotors with internal contact of pitch circles" // 5th Annual International Conference "Education Research Innovation", ERIN 2011, Slovakia, High Tatras, 13-16 aprīlis, 2011.g.; pp. 8, CD proceedings.
- N.Mozga, I.Grinevichs, "Assurance of automatic connection of plastic details by machines of non-stop operation" // VI International Materials Symposium MATERIAIS 2011, Portugāle, Universidade do Minho, Guimarães, 18.-20. Aprīlis, 2011.g.; pp. 5, CD proceedings.
- N.Mozga, I.Grinevichs, I.Brensons "Research of Influence of Collected Details form Deviation on the Accuracy of Precision Assembly" // 11th International Conference of the European Society for Precision Engineering & Nanotechnology, 11th euspen, Itālija, Lake Como, 23.-27.maijs, 2011.g.; Conference proceedings, VOL.2, 273-276 pp.
- Mozga N., Griņevičs I. „Optimization of control of automatic assembly process of parts with cylindrical shape" // 7th International Conference Mechatronic Systems and Materials, MSM 2011, Kauņa, Lietuva, 7.-9. Jūlijs, 2011.g., pp. 5, CD proceedings.
- N.Mozga, I.Grinevichs, I.Brensons "Definition of Optimal Oscillation Conditions for Vibrating Assembly on Rotors with an External Contact of Pitch Circles" // 4th Manufacturing Engineering Society International Conference, MESIC 2011, Spānija, Cádiz, 21.-23.septembris, 2011.g., pp. 6, CD proceedings.

Structure and volume of the doctoral thesis

The doctoral thesis is written in Latvian language, it contains an introduction, 7 chapters, conclusions, the list of used information sources (31 source), 37 figures, 20 tables, 72 pages.

SUMMARY OF THE DOCTORAL THESIS

Main terms

The following terms are used in the doctoral thesis:

1) ***Assembly period (process)*** – a period of time when screwing of a nut is started until the time when it is fastened with the required moment.
2) ***Comparator*** – device that can compare two values A and B. As a result of the comparison, the comparator develops output signals, whose values correspond with one of the following three situations: A is smaller than B, A is equal with B, and A is larger than B.

3) ***Electromotive force*** – work performed by external forces to transmit the charge carrier in the electric circuit. The electromotive force value is equal with the work needed to transmit a positive unit charge in the closed electric circuit.
4) ***Fastening period*** – time when fastening of a nut is started until its fastening with the required moment.
5) ***Field-effect transistor*** – type of transistor of a semiconductor device, where the output electric power is controlled with the electric field created by the voltage of input signal.
6) ***Fill ratio*** – ratio between the impulse width and its duration period.
7) ***Inductive transmitter*** – device transforming the electromagnetic changes in the electric signal.
8) ***Initial rotations*** – constant rotations of a rotator head with a value to be set.
9) ***Nut driver*** – device intended for obtaining the rigid thread connections for fastening nuts.
10) ***Oscillograph*** – device for picturing the voltage type.
11) ***Potentiometer*** – electrical device which serves to regulate and to obtain the required resistance value.
12) ***Pulse-width modulator (PWM)*** – equipment used to model pulses of various widths.
13) ***Reaction period*** – time from the moment when the trigger mechanism engages until the time when the run button is released.
14) ***Rotor head*** – rotating element of a screwdriver – nut driver where the tool for screwing screws and nuts can be mounted.
15) ***Run-out period*** – time needed to reach initial rotations from the quiescent state.
16) ***Screwdriver*** – device needed for obtaining the rigid thread connections intended for fastening screws.
17) ***Screwing period*** – a period of time when the screwdriver operates with initial rotations.
18) ***Sliding (sliding over) moment of a clutch*** – the moment to reach when the trigger mechanism engages.

INTRODUCTION

In nowaday's automated manufacturing the question concerning electric power consumption reduction is of great interest, and it leaves its impact on the final product cost. One of the options for reducing consumption of electric power is an efficient nut driver – screwdriver's use. Despite this fact, the problem is little studied yet.

1st chapter. REWIEV OF THE NUT DRIVER – SCREWDRIVER'S ELECTRIC POWER CONSUMPTION STUDIES

In this chapter is done a literature review concerning nut driver-screwdriver's power consumption issues which include:

1.1. Overview of the nut driver-screwdriver's main parameters.
1.2. The nut driver-screwdriver's power estimation method.
1.3. Electric power consumption estimation.
1.4. The study aims and objectives.

1.1. Review of the nut driver-screwdriver's main parameters

Electric motor is characterized by the following parameters: power consumption, electro-mechanical motor constants (rate constant and the torque constant), the current gradient, efficiency [17, 18].

Motor as an energy converter

The electrical motor converts electrical power P_{el} (current I and voltage U) into mechanical power P_{mech} (speed n and torque M). The losses that arise are divided into frictional losses, attributable to P_{mech} and in Joule power losses P_J of the winding (resistance R). The power balance can therefore be formulated as:

$$P_{el} = P_{meh} + P_J \quad (1.1)$$

The detailed result is as follows:

$$U \cdot I = \frac{\pi \cdot n \cdot M}{30000} + R \cdot I^2, \quad (1.2)$$

where U-applied voltage, V;
I-current, A;
M-moment acting on the electric motor, Nm;
R-rotor winding resistance, Ohms;
n-motor rotation speed, min^{-1}.

Electromechanical motor constants

The geometric arrangement of the magnetic circuit and winding defines in detail how the motor converts the electrical input power (current, voltage) into mechanical output power (speed, torque). Two important characteristic values of this energy conversion are the speed constant k_n and the torque constant k_m. The speed constant combines the speed n with the voltage induced in the winding U_{ind} (EMF). U_{ind} is proportional to the speed; the following applies:

$$n = k_n \cdot U_{ind} \ . \quad (1.3)$$

Similarly, the torque constant links the mechanical torque M with the electrical current I:

$$M = k_m \cdot I \ . \quad (1.4)$$

The main point of this proportionality is that torque and current are equivalent for the motor.

Current gradient

The equivalence of current to torque is shown by an axis parallel to the torque: more current flowing through the motor produces more torque. The current scale is determined by the two points no-load current I_0 and starting current I_A. The no-load current is equivalent to the friction torque M_R that describes the internal friction in the bearings and commutation system:

$$M_R = k_m \cdot I_0 \ . \quad (1.5)$$

The motors develop the highest torque when starting. It is many times greater than the normal operating torque, so the current uptake is the greatest as well. The following applies for the stall torque M_H and starting current I_A:

$$M_H = k_m \cdot I_A. \quad (1.6)$$

Efficiency coefficient

The efficiency η describes the relationship of mechanical power delivered to electrical power consumed:

$$\eta = \frac{\pi}{30000} \cdot \frac{n \cdot (M - M_R)}{U \cdot I}. \quad (1.7)$$

One can see that at constant applied voltage U and due to the proportionality of torque and current, the efficiency increases with increasing speed (decreasing torque). At low torques, friction losses become increasingly significant and efficiency rapidly approaches zero. Maximum efficiency is calculated using the starting current and no-load current and is dependent on voltage:

$$\eta_{\max} = (1 - \sqrt{\frac{I_0}{I_A}})^2. \quad (1.8)$$

A rule of thumb is that maximum efficiency occurs at roughly one seventh of the stall torque. This means that maximum efficiency and maximum output power do not occur at the same torque.

1.2. Nut driver-screwdriver's power estimation method

In the literature [12, 14, 21, 22, 23, 24, 25] is described the power estimation addiction from the beginning of speed and load torque, but there is no information about the energy dependence from the initial speed. This is due to the fact that the electric motor is usually used at a constant or slowly changing mode. In quickly changing regime it is not possible to measure the power using the traditional methods (using a wattmeter). Using an electric motor in short-term regimes, it is needed to calculate power for each mode separately. The engine parameters are examined only in the range that they can achieve and it is not considered possibilities to extend this range. This is done because it requires additional investments in order to develope a new equipment.

A diagram (fig. 1.1) can be drawn for every DC motor, from which key motor data can be taken[11, 14, 27].. Although tolerances and temperature influences are not taken into consideration, the values are sufficient for a first estimation in most applications. In the diagram, speed *n*, current *I*, power output *P* and efficiency η are applied as a function of torque *M* at constant voltage *U*.

Literature sources [13, 19] deal with power losses depending on the pulse modulator operating frequency and the fill ratio. In this work it was not examined because the losses constitute rather small loss-percentage of the total losses.

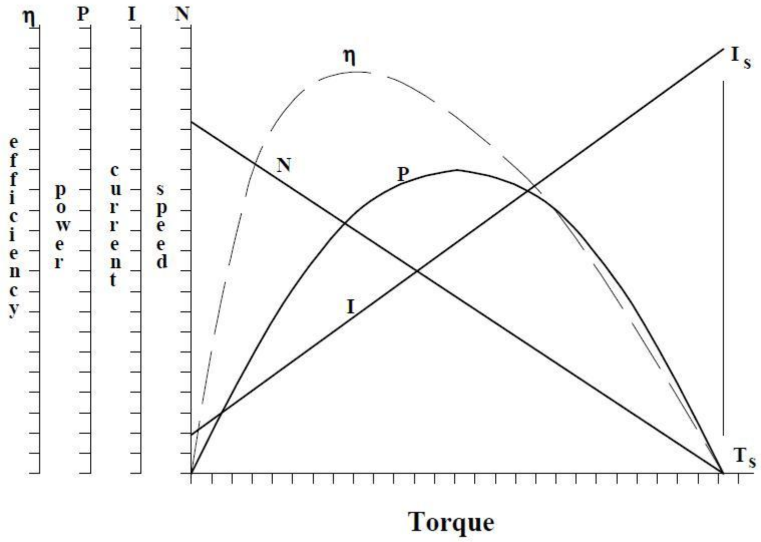


Figure1.1. Electric motor diagrams

Speed-torque line

This curve describes the mechanical behavior of the motor at a constant voltage *U*:
– Speed decreases linearly with increasing torque.
– The faster the motor turns, the less torque it can provide.

The curve can be described with the help of the two end points, no-load speed n_0 and stall torque *Ms*. DC motors can be operated at any voltage. No-load speed and stall torque change proportionally to the applied voltage. I_0 – no load current at applied voltage. This is equivalent to a parallel shift of the speed-torque line in the figure 1.2.

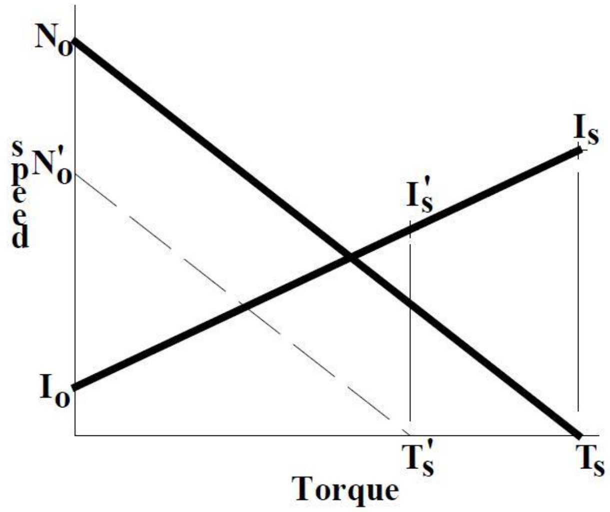


Figure 1.2. Performance Curve Conversion for Different Regulated Voltage Supplies

Between the no-load speed and voltage, the following proportionality applies in good approximation:

$$n_0 = k_n \cdot U \ . \qquad (1.9)$$

Independent of the voltage, the speed-torque line is described most practically by the slope or gradient of the curve:

$$\frac{\Delta n}{\Delta M} = \frac{n_0}{M_H} \ . \qquad (1.10)$$

The speed-torque gradient is one of the most informative pieces of data and allows direct comparison between different motors. The smaller the speed-torque gradient, the less sensitive the speed reacts to torque (load) changes and the stronger the motor.

Unlike regulated voltage supplies, batteries cannot maintain constant voltage as the torque demand increases. This is due to the internal resistance of the battery which will cause a voltage drop as the current draw increases. To convert the performance curves from a regulated voltage supply to a battery supply, use the following approximate relationship:

$$M'_H = M_H \cdot \frac{U_{sl}}{U_0} \ . \qquad (1.11)$$

Here, M_H and U_0 are the stall torque and stall voltage corresponding to a regulated voltage supply, and they are obtained from the performance curves provided by the motor manufacturer. In this equation the only measured quantity is U_{sl} which is the actual motor terminal voltage and it must be measured. Battery internal resistance R_{BAT} can be determined by the formula (1.12), firstly measuring battery voltage without load U_0, then it is necessary to connect the load and measure the battery voltage U_{sl} and consumed current I_{sl}. Also, notice that n_0 and I_0 do not change since the batteries behave the same as a regulated voltage supply under no-load condition (fig. 1.3).

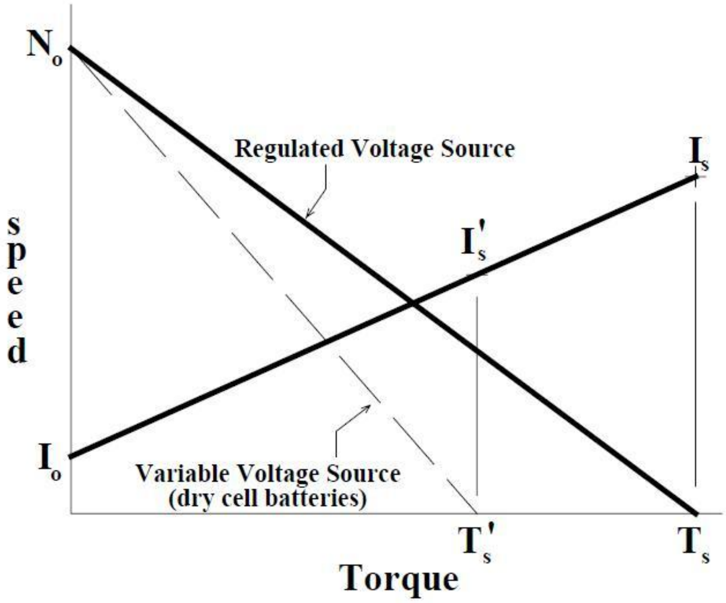


Figure1.3. Performance Curve Conversion for Battery Voltage Supply

$$R_{BAT} = \frac{U_0 - U_{sl}}{I_{sl}}. \quad (1.12)$$

1.3. Estimation of electric power consumption

Knowing what power the electric motor develops and each regime's time it is possible to determine the electric power consumption. Fixed threaded joint's assembly time consists of a rotor head's run-time, screwing time and tightening time.

In the literature sources [17, 25] are given the run-time and acceleration time formulas, but the impact on overall power consumption depending on this time is not vievwed. This is due to the fact that the electric motor is usually operated several tenths of minutes, minutes or even hours and on the total energy consumption's background accleleration time impact is very small. By running the nut driver often with large initial speed for a short period of time until a few seconds, the run-time energy consumption can take up to 80% of total electric power consumption throughout all opearting period.

There are no found measurements or descriptions, which should set out the percentage of energy is consumed by running nut driver's trigger after the required torque is achieved. There are no data on how much it would be possible to save electric power stopping nut driver's electric motor instantly when the set torque is reached. It is possible to estimate it theoretically knowing the electric motor's output data, gearbox and load parameters by which the motor is under load. This dependence is not covered, because the calculations are quite complicated and not for everyone electric motor it is possible to get the necessary technical information.

1.4. Main objectives of the study

On the basis of the literature it is possible to draw the conclusion that the industry needs to eliminate these deficiencies and to optimize the energy consumption at assembly time for fixed threaded joints. For achieving this aimthe following objectives were brought forward:

1) View screwdriver's usage conditions.
2) Calculate the tightening torque for the selected bolts.
3) Determine the electric power consumption theoretically and assembly time for the selected bolts.
4) Prepare the experimental equipment with measurement complex that is intended for research.
5) Determine the electric power consumption and assembly time for the selected bolts.
6) Make the achieved result's processing and comparative analysis.
7) Explore additional ways to reduce electric power.

2nd chapter. THE NUT DRIVER'S USAGE CONDITIONS FOR THE FIXED THREADED JOINTS' ASSEMBLY

In this chapter one of the most popular electric motor characteristic's graphical display mode is examined. Torque-speed curves graphical display is more common in technical literature directly to the DC electric motors with more power, but these schedules can also be used for electric motors with a smaller power. Torque-speed curves are created taking into account the speed of an electric motor, the rotor current, the motor output power and efficiency coefficient as a function of the electric motor moment.

2.1. Electric motor's torque-speed curves establishment methodology

1) First it is necessary to measure some of the electric motor's parameters: no-load rotational speed, current for electric motor which is under no-load, the engine stopping current and torque, the rotor winding resistance.
2) Using the obtained results it is necessary to prepare electric motor's curve (current in relation to torque and rotational speed in relation to torque). Electric motor torque constant k_m should be determined from the curve. Taking into account the previously obtained torque constant, an electric motor's speed constant k_e should be estimated. Multiplying the speed constant with a nominal voltage of an electric motor, an electric motor's theoretical no-load speed should be obtained.
3) In order to draw the electric motor's mechanical power efficiency coefficient curve it is necessary to draw up a table with the consumed power and rotational speed values at the different torque values, ranging from no-load torque till stopping torque. Electrical power values can be determined by the formula (2.1). Mechanical power is the multiplication of torque and rotational speed. Efficiency coefficient values can be found by the formula (2.2).

$$P_{el} = U \cdot I, \quad (2.1)$$

where: P_{el} - the electric motor's power, W;
U - applied voltage, V;
I – rotor's current, A.

$$\eta = (P_{meh} / P_{el})*100, \quad (2.2)$$

where η-efficiency coefficient,%;
P_{meh}-engine mechanical power, W.

2.2. Conclusions of chapter

Viewed an example of development of electric motor's torque-speed curves for which there is no available manufacturer's data information. By creating these curves it is possible to make an electric motor's power consumption calculations at the different operating modes depending on the load, torque and the operating voltage.

3rd chapter. TIGHTENING TORQUE CALCULATION FOR THE CHOSEN BOLTS

For the theoretical calculations and practical experiments in order to join two metallic plates with the size of 80x70x15 widely used 40 mm standard length bolt was selected: M5x0,8, M6x1,0, M8x1,25 and M10x1,5 with nominal diameters and metric threading steps after VS 8724-81 and VS 24705-1 [2, 9]. Based on made calculations and making round theoretically calculated required tightening torque values, we obtain: M5- 4 N*m, M6- 7N*m, M8- 15N*m and M10- 30 N*m.

4th chapter. THEORETICAL CALCULATION OF ASSEMBLY TIME AND ELECTRIC POWER CONSUMPTION

4.1. Determination of assembly period

The assembly period of thread connections, using an electric motor, depends on such parameters as acceleration of the electric motor α, inertia of the electric motor's rotor J_{ROT}, inertia of other rotating parts of the system $J_{L,}$ rotation rate of the electric motor and other parameters.

In order to determine the assembly period, first of all it is necessary to calculate acceleration of the rotor head α (4.1) at the time when the motor is being switched on till the moment when the constant set revolutions are achieved [13].

$$\alpha = 10^4 \cdot \frac{M_H(\omega)}{J_{ROT} + J_L}, \quad (4.1)$$

where: M_H – momentum developed by a motor when it is being stopped (the maximum momentum the motor can develop).

The time period t_{iesk}, when gathering rotations is done can be calculated according to the formula (4.2) [28]:

$$t_{iesk} = \frac{\omega}{\alpha}, \quad (4.2)$$

where: ω – angular rate until which the rotations are gathered.

In order to determine the screwing period t_{skr} (4.6), first of all it is necessary to determine the number of rotations n_{iesk} completed by the rotor head during the time of run-out (4.3) and the number of rotations needed n_{kop} to conduct assembly (4.5). It should be taken into account that the electric motor and rotor head have different rotation rates. The rotation ratio between the electric motor and rotor head is determined by the gear ratio A.

$$n_{iesk} = \frac{\varphi}{360 \cdot A}, \qquad (4.3)$$

where: φ – revolution angle done by the electric motor during the run-out period.

The revolution angle φ can be determined according to the formula (4.4) [26, 28]:

$$\varphi = \frac{\alpha \cdot t_{iesk}^2 \cdot 90}{\pi}, \qquad (4.4)$$

$$n_{kop} = \frac{l}{p}, \qquad (4.5)$$

where: l – screwing length,
p– thread pitch.

$$t_{skr} = \frac{(n_{kop} - n_{iesk}) \cdot 60}{n}, \qquad (4.6)$$

where: n – revolutions per minute of a rotor head.

The reaction period t_r values are determined experimentally. The normal value of the reaction period from the results of 10 measurements with the respective rotation ratio was used in calculations.

4.2. Calculation of electric power consumption

Estimating the electric power consumption, it will be calculated in 3 stages for the time period when:

1) the motor's run-out takes place,
2) screwing with constant initial rotations takes place,
3) fastening is completed but the run button is not released yet.

The fastening period will not be taken into account provided that it is too small in comparison to the overall assembly period and has hardly any effect on the final result.

The equivalent circuit (Figure 4.1) of the said equipment consists of the accumulator's battery, whose electromotive force of voltage U_{BAT}, inner resistance R_{BATT} of the accumulator's battery, resistor R_E where the voltage for determination of the electric power is measured, transistor's resistance R_D, rotor coil resistance of the motor R_R and the comparator's resistance R_{COMP}, which is equal to zero at the run time, inductance of the motor's rotor coil L, which is not taken into account in the calculations, acting in the opposite directions of the electric current flow and its value E is proportional to the motor's rotations.

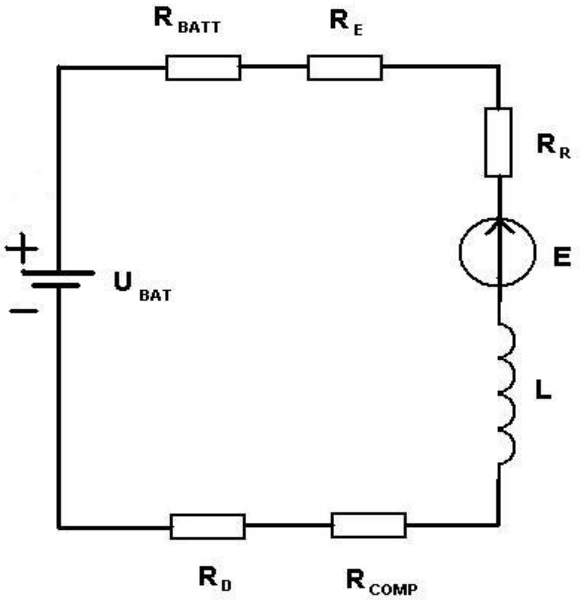


Figure 4.1. Equivalent circuitry of equipment

In order to calculate the energy consumption during the run-out period, first of all it is necessary to determine the current intensity. The run-out's initial current value I_{STALL} is provided in the motor's data sheet. The current intensity I_{START2} at the end of the run-out can be calculated according to the formula (4.7):

$$I_{START2} = \frac{U_{BAT} - E}{R_{BATT} + R_E + R_R + R_{COMP} + R_D}. \quad (4.7)$$

The electromotive force E is proportional to the motor's rotations n. It can be calculated according to the formula (4.8) [19, 21, 24, 29]:

$$E = \frac{n}{k_n}, \quad (4.8)$$

where: k_n – speed coefficient.

Now it is possible to calculate the normal current I_{START_VID} during the run-out period. Having assumed that the current decreases linearly during the run-out period, it can be calculated according to the formula (4.9):

$$I_{START\_VID} = \frac{I_{STALL} + I_{START2}}{2}. \quad (4.9)$$

Being aware of the current value, it is possible to calculate the power P_1 developed during the run-out period according to the formula (4.10).

$$P_1 = U \cdot I = I_{START\_VID} \cdot (U_{BAT} - I_{START\_VID} \cdot R_{BATT}). \quad (4.10)$$

Every accumulator's battery has inner resistance, on which the voltage drop, that is proportional to the current, occurs. It should be taken into account when calculating the power provided that the battery's voltage can drop in half or even more with large consumable electric power that would have a large impact on the final result, not considering the correct voltage value. It was already provided above how the battery's inner resistance is calculated, the formula (1.12.).

During the screwing period with a constant rate, when the pulse-width modulator is in operation, the pulse range is equal with the I_{START2} value and it remains unchanged until the fastening period. In order to calculate the normal current value, the fill coefficient D should be known. It can be determined according to the formula (4.11) [10, 15, 20, 31]:

$$D = \frac{\tau}{T}, \tag{4.11}$$

where: τ – pulse-width,

T – pulse recurrence period.

τ and T can be determined with an Oscillograph, see Figure 4.2.

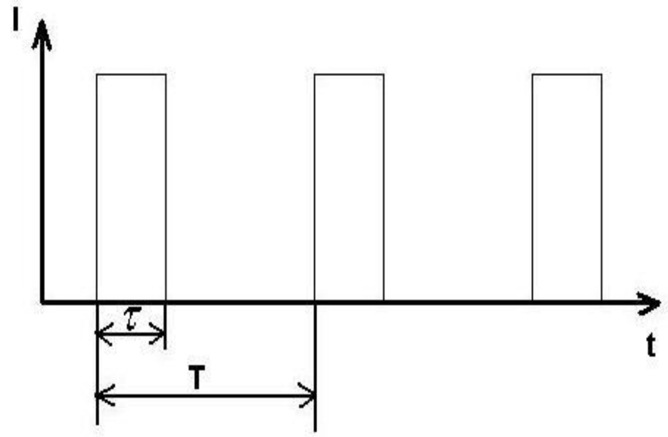


Figure 4.2. Impulses of the current

The normal current value I_{PULSE_AV} in the pulse mode can be calculated according to the formula (4.12):

$$I_{PULSE\_AV} = I_{START2} \cdot D. \tag{4.12}$$

Then the power P_2 during the screwing period at a constant rate can be established according to the following formula (4.13):

$$P_2 = I_{PULSE\_AV} \cdot (U_{BAT} - I_{START2} \cdot R_{BATT}). \tag{4.13}$$

There are 2 cases distinguished in calculation of the electric current during the reaction period, when the nut is already fastened with the set momentum but the run button is not released yet, when:

- the electric motor is unable to develop the required momentum with the set rotations and, in order to do fastening with the set momentum, a comparator engages. This situation is characteristic to low revolutions of the rotor head (300 min^{-1}, 500 min^{-1}).
- the electric motor is able to develop the set momentum and the comparator does not engage.

In case the comparator engages, the pulse modulator stops working and the transistor is opened completely with no interruption. The electric current value in the beginning of the reaction period is equal to the I_{START2} current value, which decreases gradually. When the comparator engages, full voltage and the required electric current, which is proportional to the motor’s revolutions, is delivered, but the rotor head has already stopped and the set momentum acts on the motor. The electric current decrease is justified by the fact that the electric motor starts gathering revolutions when full voltage of the battery is connected. If the electric current drops down to a certain level, the comparator would switch off and revolutions of the electric motor would decrease.

The power P_{3_COMP}, in the events when the comparator is in operation, can be calculated according to the formula (4.14):

$$P_{3\_COMP} = I_{START2} \cdot (U_{BAT} - I_{START2} \cdot R_{BATT}) . \quad (4.14)$$

To calculate the power P_3 during the reaction period, when the comparator does not engage, first of all it is necessary to calculate the speed until which the motor's rotations n_{SL} decreased (4.15) [15, 19, 29], changing the electric current value I_3.

$$n_{SL} = k_n \cdot (E - \frac{R_R M}{k_m}) , \quad (4.15)$$

where: k_m – moment constant,

M – momentum, which loaded the electric motor (mNm).

The moment constant k_m is provided in the motor's data sheet. Taking into account that there are transmission gear-wheels between the motor and rotor head, the momentum M [16, 30], which works on the motor, can be calculated according to the formula (4.16):

$$M = \frac{M_{ROT}}{A \cdot eff} , \quad (4.16)$$

where: M_{ROT} – momentum, working on the rotor head (mNm),

A – ratio between rotations of the electric motor and rotor head,

eff – efficiency of transmission gear-wheels.

Being aware of the set rotation rate until which the revolutions of the electric motor decreases, the consumable electric current value I_3 can be calculated according to the formula (4.17):

$$I_3 = \frac{E - \frac{n_{SL}}{k_n}}{R_{BATT} + R_E + R_R + R_{COMP} + R_D} \cdot D . \quad (4.17)$$

In the formula (4.17.), the value E should be taken with the set rotations, when the electric motor is not loaded.

The power P_3, when the comparator is not in operation, can be determined according to the formula (4.18.):

$$P_3 = I_3 \cdot (U_{BAT} - I_3 \cdot R_{BATT}) . \quad (4.18)$$

In order to calculate the electric power consumption during the assembly period, it is necessary to know separate parts of the assembly period, the time, when building of the electric motor's rotations t_{iesk} takes place, the time t_{skr}, when the nut is screwed with the set initial rotations and the reaction period t_r.

The time period, when fastening t_{piev} of a nut takes place is not taken into account in calculations of the electric power consumption, since it is very short and has practically no effect on the result.

The electric power E for the assembly period can be calculated according to the formula (4.19). The electric power E_{COMP} needed to reach the momentum, when the comparator engages, can be calculated according to the formula (4.20).

$$E = P_1 \cdot t_{iesk} + P_2 \cdot t_{skr} + P_3 \cdot t_r . \quad (4.19)$$

$$E_{COMP} = P_1 \cdot t_{iesk} + P_2 \cdot t_{skr} + P_{3\_COMP} \cdot t_r . \quad (4.20)$$

The graphic depiction of the obtained values is showed in Figure 4.3.

As a result of theoretical estimates for the screw bolt M10 according to the formula (4.15), it was established that it is possible to reach the required fastening period (30 N*m) starting with the initial revolutions of 1300 min^{-1}. Therefore there were 2 points depicted graphically (at 1300 min^{-1}, 1500 min^{-1}).

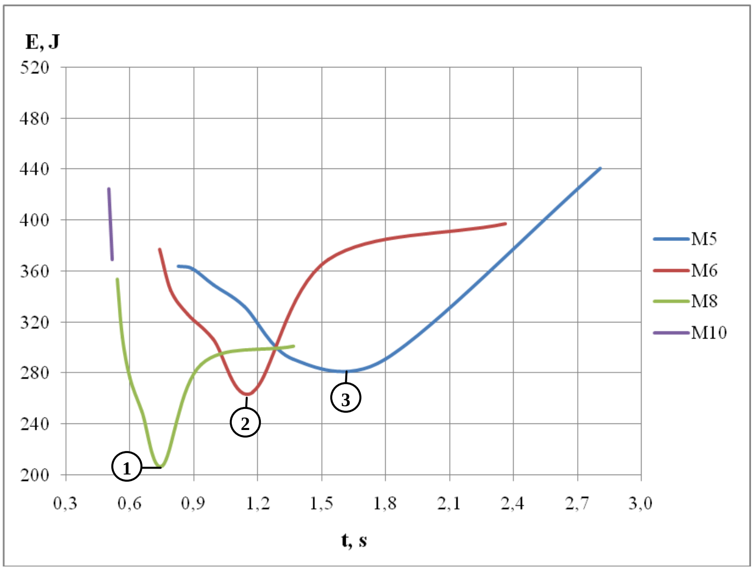


Figure 4.3. Assembly process'es theoretically estimated electric power's consumption for the bolts M5, M6, M8 un M10

4.3. Conclusions of chapter

The theoretical estimates of the fastening period and the consumed electric power were conducted, taking into account the rapidly changing processes of the nut driver in obtaining the rigid thread connections: run-out period, initial rotations, reaction period.

In the obtained curves it is obvious that in average there is more energy needed to create the screw-bolt M5 than the screw-bolt M10, making the rigid thread connection. It is related with the fact that the screw-bolt M5 has a smaller step of the thread than the screw-bolt M10, but the length of both screw-bolts is the same.

The optimum operational modes according to the electric energy consumption for a nut driver, providing the necessary fastening moment of the rigid connections of screw-bolts, are showed in Figure 4.3.:

1) For the bolt M5x40 – the 1st curve;
2) For the bolt M6x40 – the 2nd curve;
3) For the bolt M8x40 – the 3rd curve.

The optimization taking into account electric power consumption for the bolt M10x40 is not possible.

5th chapter. CONTROLLED PARAMETERS AND MEASURING QUIPMENT

In order to do the previously specified tasks, it is not only a theoretical research that is needed but it is also necessary to develop and make an equipment to conduct the experiments. Some hardware and software are needed to process the measurements and data received in the course of the experiment.

The block diagram of the equipment is showed in Figure 5.1. The equipment consists of a pulse-width modulator (PWM), which is operated by a rotary switch and a potentiometer. The power supply of the pulse-width modulator is provided from the electrical power network of 220V. The electric motor of a screwdriver is operated from the accumulator battery, where the operating voltage and electric power are controlled by the pulse-width modulator. There is a resistor with the resistance of 0,005Ω to determine the consumed current connected in series between the accumulator battery and the PWM, whose voltage is connected to the second channel of the Pico-Scope 2205 dual-channel PC Oscilloscope. The voltage of the accumulator battery is connected to the first channel of the PC Oscilloscope. The Pico-Scope 2205 is connected to the computer via the USB port. The inductive transmitter and a microphone are connected via the sound card in addition to the computer.

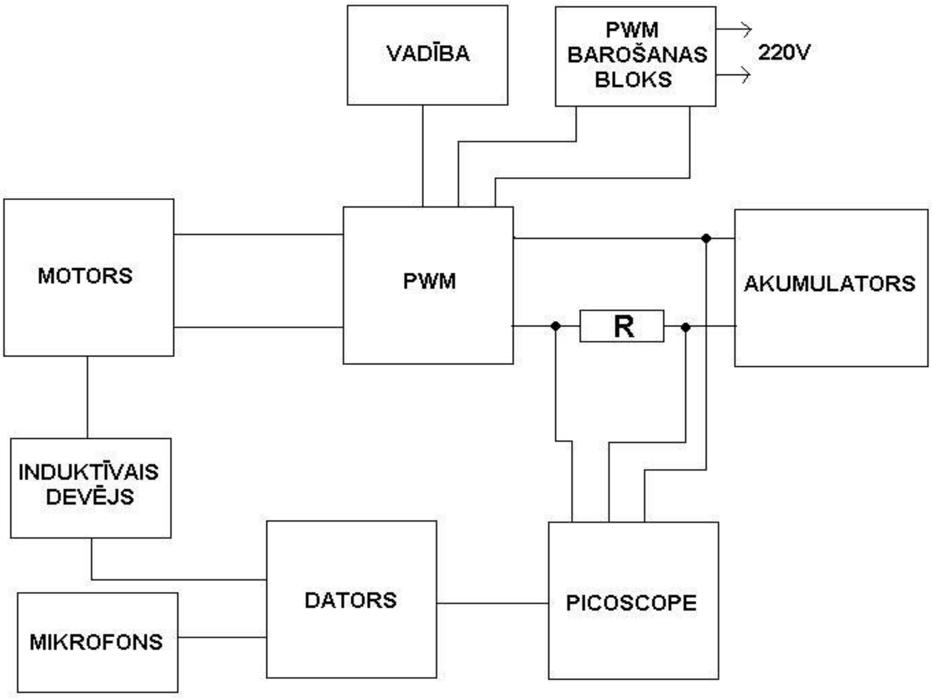


Figure 5.1. Block diagram of the equipment

Vertical nut driver with a control unit

The developed equipment (see Figure 5.2) consists of the electric screwdriver by Bosch GSR 14.4 VE-2 *13*, which is fastened to the moving element *11* of the stand. The stand is secured on the metal plate *1* of 200*300*20 mm. There is a c-clamp *3* for securing of the metal plates *4*, where a screw-bolt is inserted, fastened to the base of the stand *2*. The screw-bolt is fastened with a lock, which rests against the c-clamp. The Bosch screwdriver motor is operated by a control unit *6*. The Bosch electric screwdriver is moved in a vertical direction with a handle *12*. The dead load of 50 N of the moving element *11* of the stand has an effect on the nut during the experiment. The required sliding moment of the clutch was set with the rotary switch *9*. The fastening period was set with the dynamometric wrench of an indicator type (TOHNICHI DB50N with ¼" square according to the DIN 3120, the high accuracy +/-3% according to the DIN/ISO) after the unscrewing moment. There are the inductive transmitter *8* and the microphone *10*, which transmit a signal in the form of electric impulses to the input of the computer's sound card, installed on the stand in a short distance from the screwdriver's rotor head *7*. At a later stage the impulses are processed with the software "Sony Sound Forge Audio Studio 10". The USB Oscilloscope (Pico-Scope 2205) will be used to measure the output.

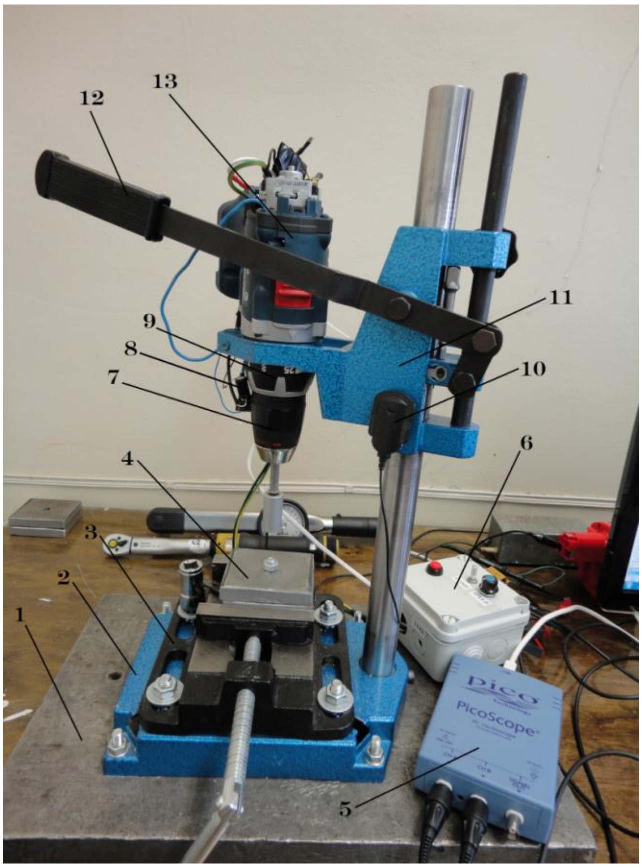


Figure 5.2. Collective view of the equipment

6th chapter. OPTIMIZIATION OF ELECTRIC POWER CONSUMPTION

6.1. The practical estimation of electric power consumption

The following corresponding parameters will be determined for the selected screw-bolts M5, M6, M8 and M10, using the Pico-Scope 6 PC Oscilloscope during the period of the conducted experiment: output (P, W) and assemblage period (t, s) that are used to determine the electric power consumption. There are 10 measurements taken in the selected measurement range of rotations (from 300 min^{-1} till 1500 min^{-1}) at every rotation value. The measurement parameters are entered in the table if the practically obtained fastening period (determined after the unscrewing moment with the dynamometric wrench Tohnichi of the indicator type) does not differ for more than 10% of the theoretically estimated value of the fastening period. The initial rotation with the value 1500 min^{-1} is not used for the screw-bolt M5 because the fastening period exceeds the permissible value at the lowest sliding position of the screwdriver's clutch. It is so because in the dynamic system the fastening period of a thread connection depends not only on the sliding over moment of the nut driver's clutch (it is set by turning the rotary switch of the nut driver) but also on an additional moment, which comes into existence from the kinetic energy of the rotor head and nut. According to the kinetic energy theorem, the given kinetic energy turns into additional fastening period [1]. The estimated moment for the screw-bolt M10 was provided only at 1500 min^{-1} and the maximum sliding moment of the screwdriver's clutch (the 25th position of the screwdriver). The graphic depiction of values for the corresponding screw-bolts is provided in Figure 6.1.

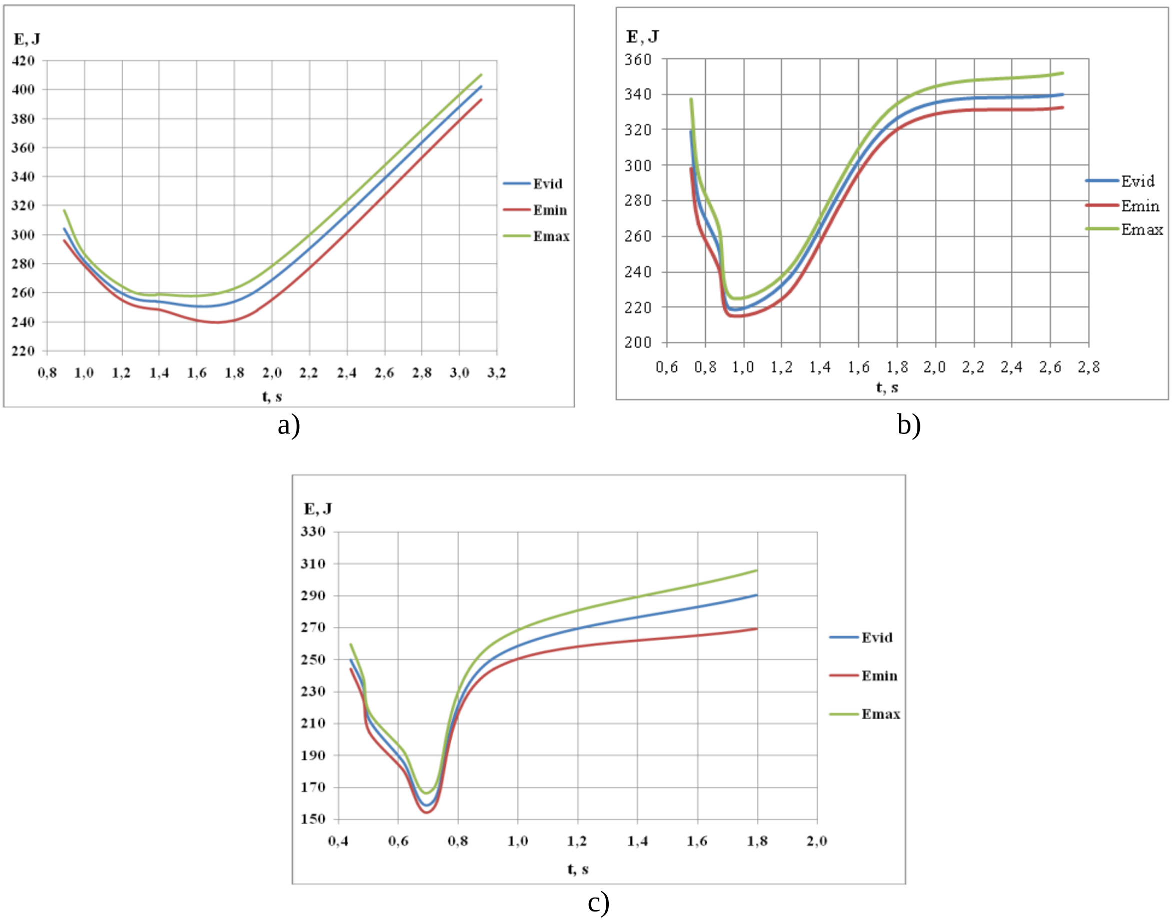


Figure 6.1. The consumption of electric power depending on assembly time for the bolts:
a - M5x0,8, b - M6x1,0, c - M8x1,25

6.2. Optimization result

The normal value of energy consumption for every screw-bolt depending on the assembly period is showed in Figure 6.2. It is obvious that the nut driver – screwdriver has such operational modes where it is possible to optimize the energy consumption after the assembly period (initial rotations). Viewing the consumable power, distributing the main points of a parabola on the sample of the screw-bolt M6 (points 1, 2 and 3 in Figure 6.2), each of these processes can be viewed separately (for other screw-bolts these processes are identical with an exception of M10, where fastening is possible only at maximum initial rotations). It can be concluded that the highest energy consumption at the maximum initial rotations is related with switching a comparator on, due to some small rotations, the screwdriver's clutch cannot slide providing the required moment, therefore the electric current is increased until the clutch slides (Stage D in Figure 6.3). Similarly higher energy consumption occurs at maximum initial rotations, which is related with large electric power consumption to start running and higher losses of electric power (Stage A in Figure 6.5). The optimal operating mode of the screwdriver according to the electric power consumption is showed in Figure 6.4, providing the required fastening moment (7 N*m) for the rigid connection of the screw-bolt M6.

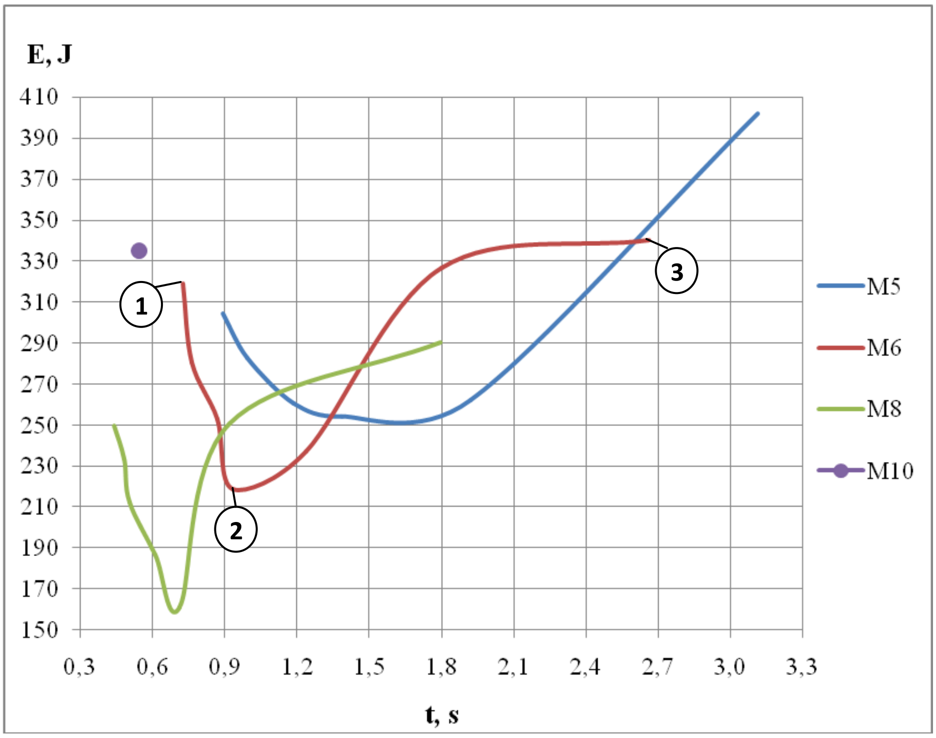


Figure 6.2. The consumption's avarage values of electric power for corresponding bolts taking into account assembly time

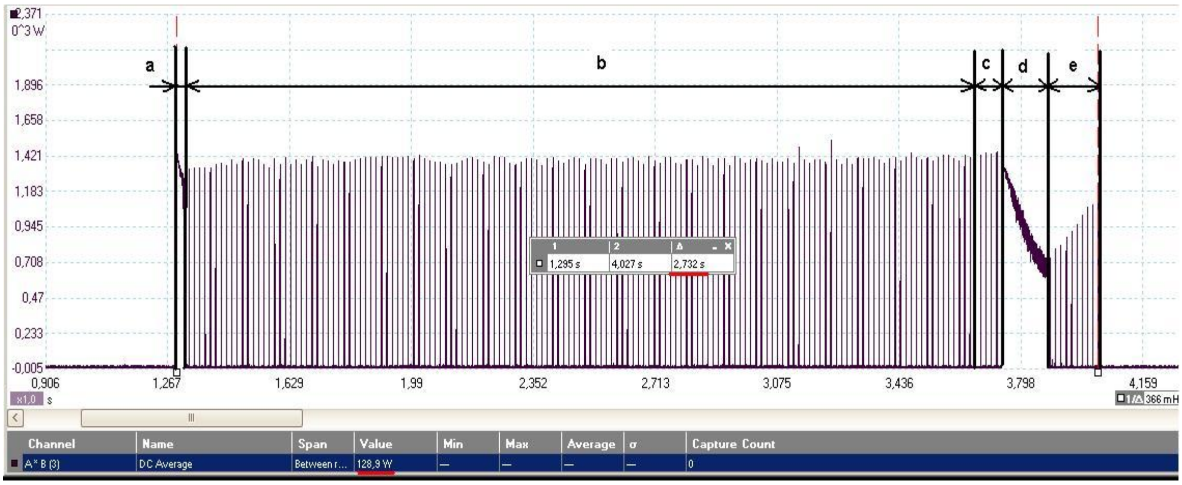


Figure 6.3. 1st point of the curve. Power consumption for the bolt M6x1,0 by the initial rotation speed 300 min^{-1}

(a – run-out power, b – motor power when the set rotation is reached, c –power after the nut's tightening, but before the comparator's work, because the set operating level is not reached yet, d –power when the comparator has worked, e – power when the comparator is turned off, as the engine picked up rotation speed, and that's why the current which is proportional to the voltage when the comparator starts working decreased)

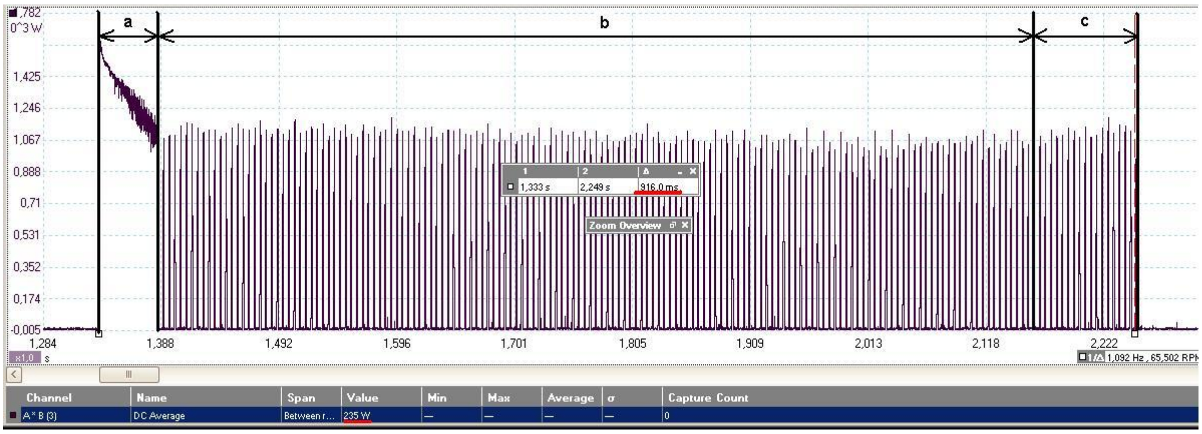


Figure 6.4. 2nd point of the curve. Power consumption for the bolt M6x1,0 by the initial rotation speed 900 min^{-1}

(a – run-out power, b – motor power when the set rotation is reached, c – power when the nut has been tightened, but the start button has not yet been released)

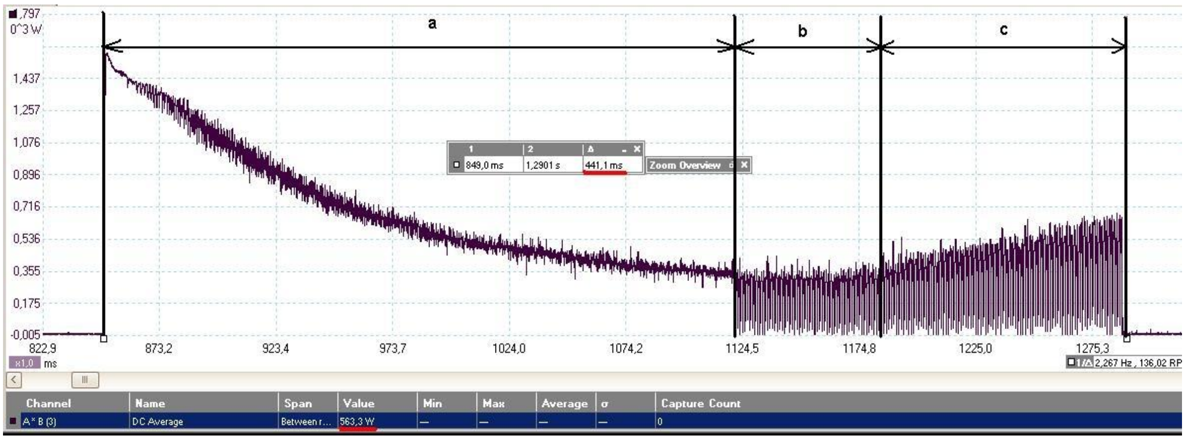


Figure 6.5. 3rd point of the curve. Power consumption for the bolt M6x1,0 by the initial rotation speed 1500 min^{-1}

(a – run-out power, b – motor power when the set rotation is reached, c – power when the nut has been tightened, but the start button has not yet been released)

6.3. Comparison of experimental and theoretical data

Comparing the theoretically and actually obtained usable energy and assembly period values, their difference does not exceed 30%. The comparison of theoretical and practical values of screw-bolts is provided in Figure 6.6, Figure 6.7, Figure 6.8 and Figure 6.9. This difference can be justified by the fact that some simplified formulas intended for electric motors with linear characteristics were used for estimates of electric power. The characteristics of the motor used in the paper slightly differ from the linear ones and they have a slight exponential disposition. The non-linearity of the electric motor's characteristics can be reduced when using a continuous source of voltage instead of the accumulator battery. Comparing the difference of results it is obvious that at lower initial rotations (300 min^{-1}, 500 min^{-1}), an error is the smallest, then it increases (900 min^{-1}) and later drops again slightly (1300 min^{-1} , 1500 min^{-1}). The small difference at low initial rotations can be justified by the fact that the characteristics are practically of linear nature. In its turn, at 900 min^{-1} the real non-linear characteristic differs most of all from the theoretical one. The theoretical estimates also do not consider such electric motor values as inductance of rotor coils L, the resistance of rotor coils depends on their temperature, the battery voltage and the electric power's dependence on its temperature, losses of electric power depending on frequency. With high and frequent running currents of electric motor, the temperature of electric motor and battery can increase even several times. Of course, a certain role was played also by an error of measuring instruments and the reading error, which contributed to developing of a difference between the theoretical and actual results.

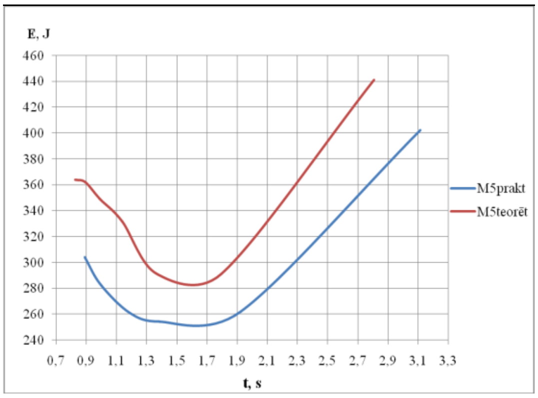


Figure 6.12. Comparison of theoretical and practical values for the bolt M5x0,8

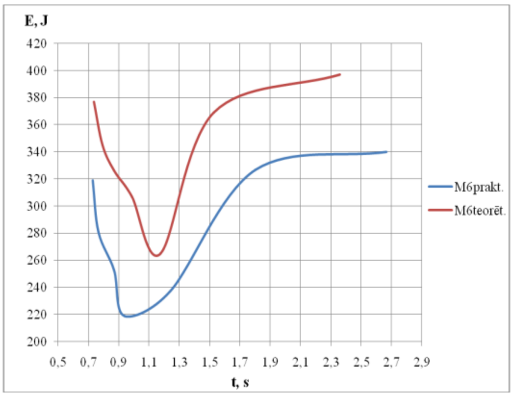


Figure 6.13. Comparison of theoretical and practical values for the bolt M6x1,0

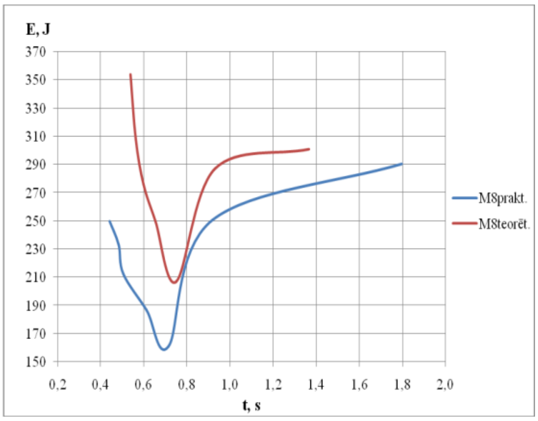


Figure 6.14. Comparison of theoretical and practical values for the bolt M8x1,25

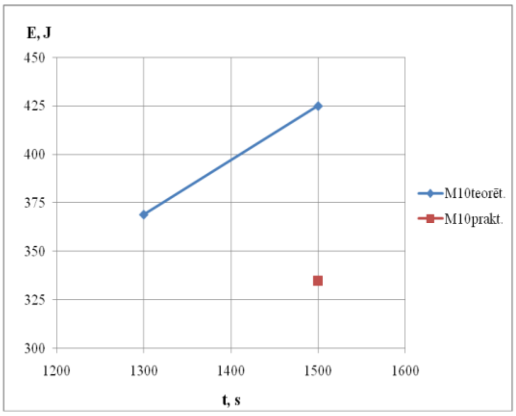


Figure 6.15. Comparison of theoretical and practical values for the bolt M10x1,5

6.4. Conclusions of chapter

On the basis of the obtained results it can be concluded that the nut driver – screwdriver has such operational modes that permit performing of the electric power optimization depending on the assembly period. The most economical mode of a screwdriver is at such minimum initial rotations requiring no additional electric power (involving of the comparator), providing fastening of a nut with the corresponding moment.

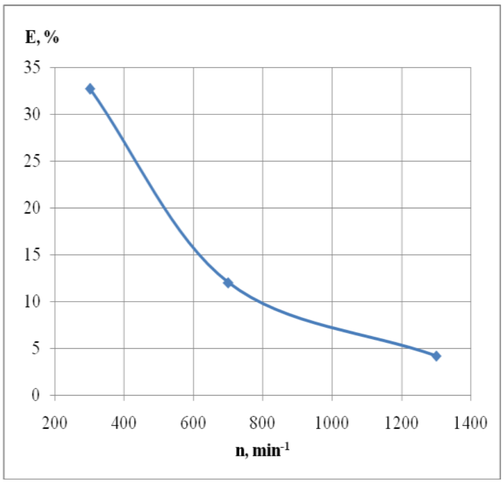
Although the difference between the theoretical and actual values measures up to 30%, nevertheless the optimum modes of the screwdriver actually matched in the sense of electrical power consumption. It should be noted that the theoretical estimate is much more time consuming and less accurate, therefore it is preferable to take practical measurements to determine the electric power consumption. Taking into account that in the computerized assembly usually using the maximum rotations of a rotor head of the screwdriver – nut driver, performing optimization of the energy consumption after the assembly period, decreasing is obtained:

1) For the bolt M5x40 with tightening torque 4 N*m is till 16,4%;
2) For the bolt M6x40 with tightening torque 7 N*m is till 31,4%;
3) For the bolt M8x40 with tightening torque 15 N*m is till 35,5%.

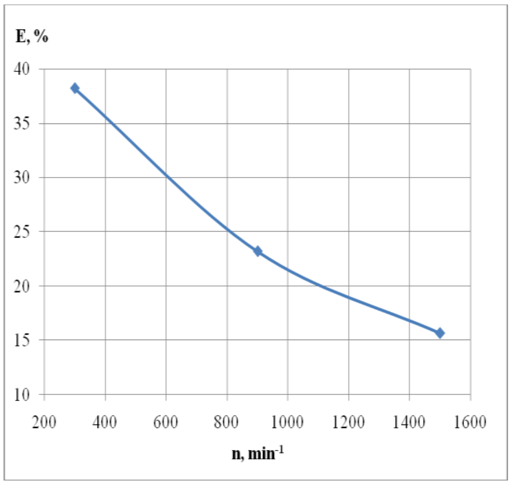
7th chapter. ADDITIONAL ACTIONS FOR THE REDUCTION OF THE ELECTRIC POWER

7.1. Cutting of electric power when the trigger mechanism engages

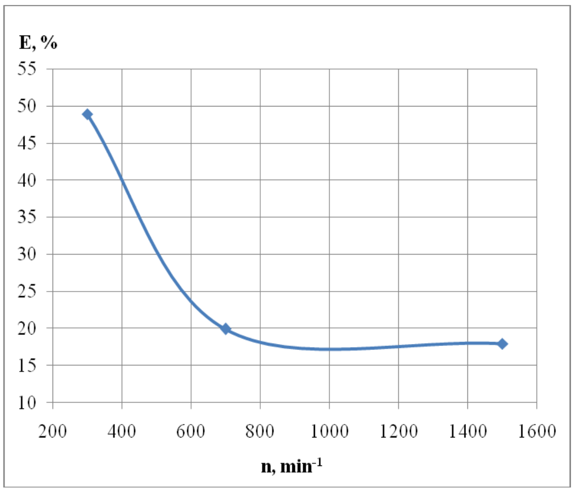
During the measurement period it was observed that reaching the required fastening moment when the trigger equipment engages, the energy is consumed to apply breaks on the clutch when the reaction period passes until the run button is released. In Figure 7.1 the possible electric power economy in % is showed for the screw-bolts M5x0.8, M6x1.0, M8x1.25 when the delivery of electric power is cut off after the first click of the trigger mechanism (until the reaction period) at the corresponding initial rotations (minimum, maximum and optimum).



a)



b)



c)

Figure 7.1. The savings of electric power (% from the initial rotation speed)for the bolt: a - M5x0,8; b - M6x1,0; c - M8x1,25

7.2. Conclusions of chapter

There is a way for additional energy decrease discovered, performing assembly of the rigid thread connection, cutting the electric power supply off (e.g. supplementing the screwdriver – nut driver with the moment transmitter at which the electric motor is turned off). When the trigger mechanism engages, the additional energy is consumed by the screwdriver's clutch overpowering the friction until the run button of the electric motor is not released, the longer is the reaction period, the more energy is consumed. In the optimum mode (in the sense of electric power consumption and assembly) it would let us obtain:

1) For the bolt M5x40 with tightening torque 4 N*m is till 12%;
2) For the bolt M6x40 with tightening torque 7 N*m is till 23,2%;
3) For the bolt M8x40 with tightening torque 15 N*m is till 19,9%.

CONCLUSIONS

The following conclusions can be drawn on the basis of the paper's results:

1) Conducting a literature review, it was established that there was no adequate attention paid to dependence of the power consumption on the initial rotations of the screwdriver's rotor heads and the obtainable fastening moment of the screw-bolt in the information sources available at the time of developing this paper. As well as the motor parameters were studied only within such a range of rotations they can reach and there were no possibilities of increasing this range reviewed. There is also a lack of information on the electric power consumption in the variable operational modes of a screwdriver. There is no adequate attention paid to the electric power consumption during the run-out period. There are no data whether any electric power can be saved, stopping the electric motor of the screwdriver as soon as the set moment is reached.
2) It is possible to perform the estimates of the consumable power of an electric motor at different operational modes depending on the load moment and operating voltage, creating a characteristic of moment – speed.
3) The theoretical estimates of the fastening period and consumed electric power were performed, considering the rapidly variable processes of the nut driver in obtaining the rigid thread connection: run-out period, initial rotations, reaction period.
4) The experimental device with the integrated measurement equipment to perform a research was developed. It should be specified that the innovation is measuring of rotations and determining of time, using the sound card of a computer.
5) The nut driver – screwdriver has such operational modes that permit performing of the electric power optimization depending on the assembly period. The most economical mode of a screwdriver is at such minimum initial rotations requiring no additional electric power (involving of the comparator), providing fastening of a nut with the corresponding moment.
6) The theoretical estimate is much more time consuming and less accurate, therefore it is preferable to take practical measurements to determine the electric power consumption of the nut driver.
7) Performing assembly of the rigid thread connections, when the trigger mechanism engages, some additional energy is consumed by the screwdriver's clutch overpowering friction. It is possible to reduce the electric power consumption, cutting the electric power supply off (e.g. supplementing the screwdriver – nut driver with the moment transmitter at which the electric motor is turned off).

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