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Development of electric impact drills and investigation of the efficiency

Thesis of Ph.D. dissertation

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Introduction

The impact drill is the most known from the electrical power tools. In the last decade the impact drill construction and function has been slightly changed. The development focused on decrease of the size and the weight, ease and comfortable of the use and to extends the functions. Not mentioning the hammer drills, the inner mechanical construction of the impact drills have not changed dramatically. The gearbox between the chuck and motor, the alternating impact mechanism remained unchanged during the last decades. The impact mechanism of the recently developed machines due to changed requirements needs to be investigated and redesigned.

1. Objective of the research

Based on the literature and the available theories at Robert Bosch Power Tools, taking into account the results published so far and their shortcomings I chosed the following objectives: Investigation of the effects on the impact energy of the geometry of the ratchet of single speed impact drills and mechanical parameters of the machine. Examination of the mechanical parameters and taking constructional conclusions. Investigation of the formation and propagation of elastic wave arisen in the impact mechanism. Construction of a simplified mechanical model, programming of the own developed finite element solution and investigation of the parameters influencing the impact energy. Make software based finite element calculation based on CAD model. Experimental validation of the results of the theoretical models based on measurement of efficiency of concrete drilling of impact drills. The percussion drill development and evaluation of information collected during manufacturing and warranty analysis, a systematic description of the methodological tools for product development.

2. Literature review

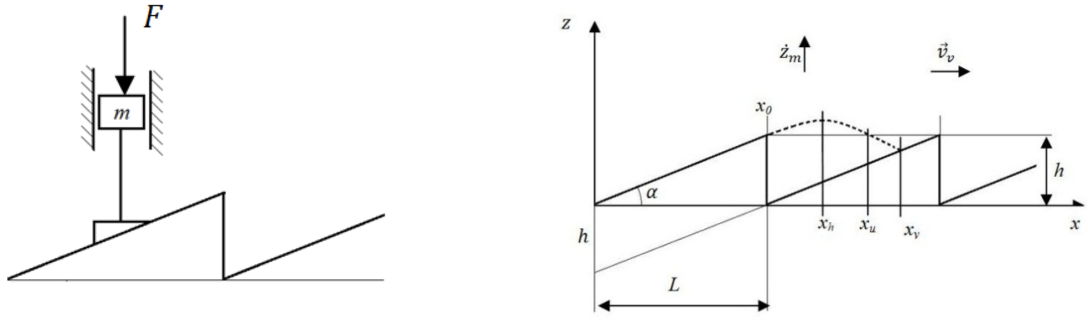
The first part of the paper machine equipment design methodology, development tools deals. Multinational companies' product development processes become important results of the systematic science of mechanical engineering. The theory of machine design is subject of researches from the 1920 in Germany. F. Kesselring already published in 1937 the various construction evaluation procedures. In 1942 [1] he demonstrated the technical and economic construction variants evaluation process. This has been described in the VDI 2225 [2] later on. Hugo Wögerbauer suggested on his book in 1943 [3] that the design task must be divided into sub-tasks. The founders of the school of Ilmenau were Werner Bischoff, Arthur Bock and Friedrich Hansen. They continuously dealed with the constructor education, which describe in the [4]. First publication in 1952, "Konstruktionssystematik" that means design system term in G. Biniek work [5]. F. Hansen has been dealt with methodology of design in the 1950s. He summarized his design system in 1965 in his book [6]. The Berlin design school founded by Wolfgang Beitz. His work „The Theory and Practice of Machine Design" has been published together with the Darmstadt school's founder, Gerhard Pahl [7]. Vladimir Hubkais the first who recognized the need for the Theory of Technical Systems, TTS [8] ,because of an existing theory allows the development of appropriate methods [9]. This was later confirmed in 1965 [10] by Klaus G. V. Hubka V. published in1992 together with the Austrian-born Ernst W. Ederrel jointly the book "Einführung in die Konstruktionswissenschaft" (Introduction to construction science) [11], [12]. Karlheinz Roth using the development of computers, has been introduced in 1974, at the Braunschweig University of Technology the computer-aided design [13]. Saulovich Genrikh Altshuller is the creator of the TRIZ (theory reshenie Izobretatel'skih Zadach), so the Inventive Problem Solving Method [14]. The WOIS (Wiederspruchorientierte Innovationsstragegie) was an experiment that unified the TRIZ methods and theories of the German design that is a contradiction oriented innovation strategy, from H. Linde and B. Hill in 1993, describes the method developed by them [15]. The Budapest designer school is the most important In Hungary, dealing with product design science and IT system research. The founder of the research area in Hungary is Bercsey Tibor, teacher of BME, whos works [16], [17], [18], [19] can be mentioned. Already in 1979, he publisehd about the use of computers in machine design in [22] with co-authors. The Miskolc design school founded by József Tajnafői and Zénó Terplán. Döbröczöni Adam deals with the application of general principles of mechanical engineering in product design [20], [21] which was introduced in education by Kamondi Laszlo [20], [21]. József Tajnafői developed several major methods in connection with the machine tool design methodology [23], [24], [25]. The Today's large companies development processes include a number of independent methods, which have evolved in recent decades, and widespread. The cause-effect relationship method, and its use in the design and production Kaoru Ishikawa was presented in 1968 [26]. The quality function deployment (QFD) is a method by which the user needs can be expressed in the form of quality standards. The method was developed by Yoji Akao in Japan in 1966 [27]. The failure mode and effects analysis (FMEA) was one of the first systematic error analysis method used, developed by the U.S. defense industry. Toyota developed the method and created the DRBFM system, and for first officially published in March 2013 [28]. The production and assembly design methodology, ie, the DFMA developed for research of automated production in the seventies. In 1970 is a guide book was publisehd [29] in the edition of the University of Massachusetts. G. Boothroyd B. Wilson and his colleagues at the University of Massachusetts addressed first in a three-year research program to improve design for manufacturing [30], [31]. B. Lundberg and M. Okrouhlik published in 2000 [32] the effeciency of rock percussion drilling of three-dimensional finite element model of a hollow drill method. The authors concluded that for impact drilling in the three-dimensional case, generally 4% less efficient than the one-dimensional results, the difference is negligible. Also in 2006 an article published by B. Lundberg and M. Okrouhlik [33] about the process of percussive drilling of rock and examined the transfer of wave energy. In this study, the finite element method is applied with three-dimensional models. They conclude that the radiated energy into the rock is much more affected by the rebounding drill at the expense of kinetic and potential energy is created. In 1999, L.E. Chiang and DA Elías their published paper [34] dealt with the case of percutaneous drilling, which presents an alternative solution. The drill-rock interactions were modeled by a linear spring and a variety of slots, validated by its own drilling experiments. In 2011 [35] studied experimentally drilling and mechanical properties of brittle rock-like materials.

3. Development process of impact drill

Under the development process of the power tools we mean a long, often several years complex process during which a new product from a concept reach to commercial distribution. In the pre-development phase, product ideas based on market needs and data, product concepts are developed. The aims of development phase is selecting an optimal solution based on the demands, and then the implementation of the concept, design of the machine components and design the manufacturing process. The product development process can be divided into four phases: conceptual design phase, implementation phase, pre-production phase, the phase of market opening. The maturity of product construction during the project is followed and measured by the tests in the test plan. In the first phase of the process, based on the previously established structure and the found solutions for the function of the physical features, and taking into account the different design aspects the design of the parts of the machine can take place. In the second phase of the process based on CAD model drawings are made for all parts, on which the different suppliers are able to manufacture them. After all the parts from suppliers considered final, the project will enter the pre-production phase. The final phase, the aim is to ramp-up production, the training of employees and a large amount of manufacturing of tools with which the selling can start. During the construction of the various stages of product development support tools are available, by their use, any defects in development work are avoided or their impact reduced.

4. Analysis of percussion mechanism

The movement of impact drills is created by a couple of spur gear hitting and sliding each other. It is assumed that the rotational is constant, the rotational motion of the collisions do not affect the uniformity. Ratchet movement caused by the collisions of the gear and fuselage forced axial movement.



a) *b)*

5.1.figure: a)model of single degree of freedom rigid system b) art of movement

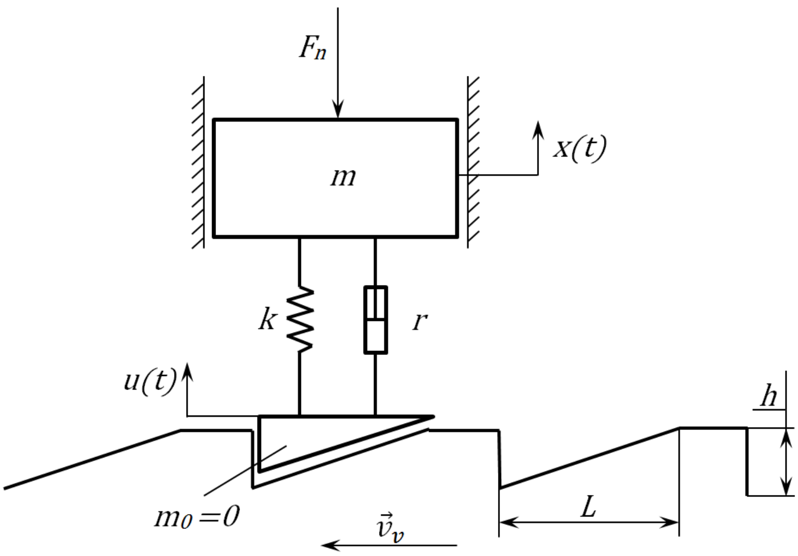
The impact energy, and through the drilling efficiency is determined by the energy of the collisions. The impact passed by the mechanism will depend upon the weight of the machine, axial speed before the collision. First approximation, the motion is described as typical of the oblique projection. The movement is divided into two sections: one slip and a flight phase. The solution is available from the equation of motion of a flying by double integration, the vertical displacement:

$$z_m = -\left(g + \frac{F}{m}\right)\frac{t^2}{2} + \frac{R\omega h}{L}t + h\,. \tag{5.2}$$

At the end of the flight stage axial speed of the machine calculated the energy of impact, ie the impact energy:

$$W_{\ddot{u}} = \frac{m}{2}\left\{\sqrt{2hF_n\left[\operatorname{mod}\left(\frac{\omega^2 hz_r^2}{2\pi^2 F_n}\right)+1\right]} + \frac{z_r \omega h}{2\pi}\right\}^2. \tag{5.3}$$

It is visible from 5.3 that the impact energy is affected only by the number and height of cogs of ratchet. The impact energy function is gradually inclining, saw teeth form as the function of pressing force due to jumping over of the cogs. During percussion drilling, due to friction occurring on the slope by the effect of increasing compressive force, the machine speed will be reduced, so we got the discharge performance curve maxima, which provides the optimum for impact drilling. The large mass rotor and stator in the drilling machine is flexibly connected to each other with the ratchet. Dynamic model of the previous section was modified in that we assume damped elastic connection between the ratchet and flying weight. The structure is modeled by a single degree of freedom; displacement excited vibrating system that takes into account the separation as well. The resulting movement is determined by ratchet slope geometry and the relative rotational speed until the ratchet and the incline is separated, that is exerted by the spring and damping force is less than zero.



4.12. figure: Single degree of freedom, elastic model of impact drill

The movement of the system is described with two equations [36]:

$$\begin{cases} m\ddot{x} + r\dot{x} + kx = ku + r\dot{u} - F, & \text{ha } [k(x-u) + r(\dot{x} - \dot{u})] < 0 \quad (5.4) \\ m\ddot{x} = -F \quad , & \text{ha } [k(x-u) + r(\dot{x} - \dot{u})] \geq 0 \quad (5.5) \end{cases}$$

Equation (5.4) is valid while slipping on the slope, and the equation (5.5) refers to the phase of flight. Mechanical damping and spring constant used in the model was based on a specific machine noise measurements carried out and high-speed camera images. The results show clearly that during the percussion drilling machine, vibration generated by ratchet carry lower frequency vibrations, causing consecutive pulses of magnitude difference. We can not neglect the flexibility and the the mass of components participating in the production of the impact energy by the examination of effectiveness of the percussion drill. The pulse created on the ratchet, spread like a wave and passed to the end of the drill bit, where the the rock is processed. For the description of phenomenon is a simplified prismatic bar model is assumed. Consider the dynamics of an elementary length of the rod section. The bar element length dx, the rod member displacement u (x, t) on the left face of the rod member awakening bar force N (x, t) and the right N (x + dx, t). Creating Fourier transformation of N (x + dx, t) force and neglecting the higher then linear order members the rod directional lot of momentum [36] following form can be written:

$$\ddot{u}dm = -N(x,t) + N(x,t) + \frac{\partial N(x,t)}{\partial x}dx. \quad (5.6)$$

The valid form of the well-known wave equation for prismatic beam longitudinal waves:

$$\frac{\partial^2 u}{\partial t^2} = v_H^2 \frac{\partial^2 u}{\partial x^2}. \quad (5.7)$$

The (5.7) wave equation ordered to zero and derivative operations can be highlighted in the following figure:

$$0 = \frac{\partial^2 u}{\partial t^2} - v_H^2 \frac{\partial^2 u}{\partial x^2} = \left(\frac{\partial^2}{\partial t^2} - v_H^2 \frac{\partial^2}{\partial x^2}\right) u\,. \quad (5.8)$$

The rate of end cross-section can also be written of deformation occurring there:

$$v(L,t) = \frac{\partial u(L,t)}{\partial t} = -v_H \frac{\partial u_I}{\partial x} + v_H \frac{\partial u_R}{\partial x}. \quad (5.9)$$

Completed the conversion to the following differential equation gives:

$$\frac{dF}{dt} + \frac{F \cdot k_{pl}}{Z} = -\frac{2N_i}{Z}. \quad (5.10)$$

where k_{pl} is the plastic rigidity of the rock.

This differential equation contains at the end of the drill bit, the beam force at the wall from the progressive wave, which is determined by the relationship between shock pulses per volume of rock machining. The solution of the equation:

$$F(t) = -\frac{2}{Z}\int_0^t e^{-\frac{k_{pl}}{Z}(t-\tau)} N_i(\tau)d\tau = -\frac{2}{Z}\int_0^t e^{\frac{k_{pl}}{Z}(\tau-t)} N_i(\tau)d\tau \ . \tag{5.11}$$

Based on this correlation, the highest value at end of the rod working pulses can be achieved with exponentially changing incident pulse shape. The shape of the pulses generated by the percussion drill ratchet in our case structurally difficult to influence. In the following, we examine the effect of wave propagation hammer drilling efficiency of the piecewise constant rod. To do this, set in equations for the wave equation (5.7) finite element overview! The wave equation (5.7) is obtained by multiplying δu (x) is integrated into a virtual displacement of the rod and the volume of the following equation:

$$\int_0^L \frac{\partial^2 u}{\partial t^2}\delta u A dx - \int_0^L v_H^2 \frac{\partial^2 u}{\partial x^2}\delta u A dx = 0\,. \tag{5.12}$$

The studied range is divided a of n^e two-node finite element! The movement is linearly approximating each element:

$$u^e(\xi) = \left(1-\frac{\xi}{L^e}\right)u_i + \frac{\xi}{L^e}u_j = \begin{bmatrix}1-\frac{\xi}{L^e} & \frac{\xi}{L^e}\end{bmatrix}\begin{bmatrix}u_i\\ u_j\end{bmatrix}, \tag{5.13}$$

where the local coordinate ξ, L^e is the rod by rod member with the length of the rod member u_i and u_j endpoint displacement (nodal displacements). Using the notations introduced Substituting the expressions discrete shape of the wave equation:

$$\sum_{e=1}^{n_e}\delta \boldsymbol{q}^{eT}\int_0^{L^e} \boldsymbol{N}^{e\boldsymbol{T}}(\xi)\,\boldsymbol{N}^e(\xi)A^e d\xi \ddot{\boldsymbol{q}}^e + \sum_{e=1}^{n_e}\delta \boldsymbol{q}^{eT}\int_0^{L^e} \boldsymbol{B}^{\boldsymbol{T}}(\xi)v_H^2\,\boldsymbol{B}(\xi)A^e d\xi \boldsymbol{q}^e = \frac{F(t)}{A\rho}\delta u_1, \tag{5.14}$$

where $\boldsymbol{N}^e(\xi)$ of the finite element approximation matrix $\boldsymbol{B}^e(\xi)$ of the finite element displacement deformation matrix, and $\boldsymbol{q}^e$ of the element nodal displacement vector. Using the normal pattern of summation, the following matrix equation is obtained by the finite element method:

$$\delta \boldsymbol{q}^T[\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q}] = \frac{F(t)}{A\rho}\delta u_1, \tag{5.15}$$

where $\boldsymbol{q}, \ddot{\boldsymbol{q}}, \delta\boldsymbol{q}$ the structure of nodal displacements, accelerations and vector of the variation of the displacements. The generalized structure weight matrix ***M***, the structure of the generalized stiffness matrix ***K***. The variation of nodal displacements are arbitrary, so

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = \boldsymbol{f}. \tag{5.16}$$

matrix equation is valid, where $\boldsymbol{f}^T = \left[\frac{F(t)}{A\rho} \; 0 \ldots \ldots \ldots \; 0\right]$ vector loads of the structure. Numerical solution of the equations of motion of the trapezoidal method is used. The software is made such calculations in Scilab. It can be observed that the measured contact force at the tip drill, which performs the conversion between the first pulse is dominant. As the magnitude and time course of shaping cause real work. The incoming pulses on the output shaft passes through, but due to the change of cross section and the swing weight a number of reflections are created. The multiple reflected waves and the oscillating mass to accelerate due to the energy dispersion, thus reducing the size of the pulses required for drilling. Reducing the weight of the chuck part of the first pulse magnitude is approximately 40% increase, which means that the chuck weight reduction can be achieved by improved efficiency. A simplified finite element model shown in Abaqus commercial software is certified. The tested model of the drilling machine gear, shaft drilling, the chuck body, the chuck jaws, chucks the bit rings included. The pulse propagation in finite element simulation spectacularly follows physical phenomena observed in the preceding subsection. Nature of the wave reflected from the impact good agreement with the results of simplified finite element models.

5. Application of the results, further objectives

I intend to give details for the process and design tools described in dissertation in a separate manual. This may be further developed with contrasts figures and detailed process descriptions with an easy to use, Hungarian product development guidebook. Conclusions described in the design chapter is based on the number of failure phenomena that occurred during the testing and use impact drills. These failures entirely appropriate to collect, and the various failure photos possible root causes combined. These relationships can be summarized in a single system, in which the information would be recorded for bullet or matrix format. It shows an interesting area of research to study the behavior of the model of percussion mechanism described with different geometries and with ratchet cog numbers. As the percussion drilling the drill bit loaded to torque, the model developed by the effect of torsional stress seems to be necessary. In this case the torsion waves specification requires the examination of the nature of the drive and the bit friction. Measuring the efficiency of percussion drilling can be improved measuring waves in the bit. Conventional strain gauge measurement of rotary hammers drill shaft needs further development, as in the case of percussion drills the rotation of the drill bit does not allow this type of measurement.

6. Summary

In this dissertation the development methods and tools of electric impact drills are presented, construction experiences are explained. The influencing construction factors on the efficiency of impact drilling are investigated. After the systematization and introduction of the development of impact drills, the construction of one-speed drills is described. In the review of literature, the states and results of classic design schools are summarized. The known design methods and tools, used currently in the industry are expounded. The development and design process of impact drills and power tools are presented. Support methods of product development are listed and described. Based on the author's design leader experiences and the available literature, the useful construction knowledge of impact drills is presented. To investigate the efficiency of percussion drilling a one-degree of freedom mechanical model is built. Based on the equations, the effects of the influencing parameters are calculated in case of an existing design. For the validation of the result, a measurement series was performed. With the improved elastic mechanical model the phenomenon of vibration on different frequencies following that the excitation is shown. To determine the parameters of the model and to evaluate the results high speed camera records, and noise measurement were done. For the calculation of mechanical model a software was developed. The effect of geometry of impact mechanism on the wave propagation was examined. The mechanical model was built to investigate the wave equation with finite element method. The software was developed. The results of the software were compared with a simulation done with commercial software on the original 3D data.

7. New scientific results

T1. For the investigation of the influencing parameters of the efficiency of impact drills I have created a one-degree-of-freedom rigid mechanical model that is suitable for the determination of impact work. I have proved that during impact drilling, depending on the rotational speed and pushing force, cog jump can occur. I have stated that the pushing force and the efficiency have got optimum, because of the drop of rotational speed, in case of machines without speed regulation. The experiments made for the validation of the calculated results have proved the assumed behaviour of the model.

T2. For a better approach of the drilling efficiency I have developed a one-degree-of-freedom elastic model, and worked out the simulation software. The model is suitable to calculate the magnitude and temporal change of the impulse during percussion drilling. Based on measurements and calculation, I have established that with high rotational speed and low pushing force indicate a vibration of the tool which has different frequency than the exciting frequency. The phenomena have caused the deviation of the following impulses.

T3. For the investigation of the wave, propagating in the impact mechanism, I have developed a one-degree-of-freedom finite element model and software. It is modelling the impact mechanism with bar consist of different diameter steps. The contact of processed material and tool is taken into consideration with linearly hardening, plastic-elastic material and single side contact. The calculation result has shown that the possible decrease of changing cross-sections and the chuck as a vibrating mass increase the efficiency of impact drilling.

8. Publication of the thesis

[KJ 1] Kakuk József: An assessment of the efficiency of percussion drills, ICT-2012, 13th International Conference on Tools, 27 – 28 March 2012, Miskolc, Hungary

[KJ 2] Kakuk József: Ütvefúrógépek ütő mechanizmusának dinamikai vizsgálata, Géptervezők és Termékfejlesztők XXIX. Országos Szemináriuma, 2013. november 7.-8. GÉP, 2013/7., LXIV. évfolyam, ISSN 0016-8572, pp 72-77.

Presentations held in the field of thesis

[KJ 3] Kakuk József: Product development process, Technology Center Engineering Seminar, Vonyarcvashegy, 2013. november 12.-13.

[KJ 4] Kakuk József: Ütvefúrógépek fejlesztése a hatékonyság figyelembe vételével, Géptervezők és Termékfejlesztők XXVIII. Országos Szemináriuma, 2012. november 8-9.

[KJ 5] Kakuk József: Kéziszerszámgépek fejlesztési folyamata és a tervezést támogató eszközök, MTA Műszaki Tudományok Osztálya Gépszerkezettani Tudományos Bizottságának ülése, 2013. november 28., BME Járművek és Járműrendszeranalízis Tanszék

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