The design optimisation of the self-locking moving device using CAD software

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Abstract. In the paper results of the design optimisation process for the self-locking moving device using CAD software are shown. As the object of the design optimisation the plier barrier subassembly was selected. The decision about selecting of the plier barrier subassembly as the optimisation object was made taking into account its importance for the device operating and safety. The optimisation process was carried out in Autodesk Inventor software. As a result, a new modified design of the plier barrier was developed. The design was next used for manufacturing of the self-locking moving device prototype. The prototype device was subjected to load mechanical tests in order to check its mechanical strength and the plier barrier clamping force effectiveness. The results of the mechanical tests in the content of the paper are presented in whole. The carried out experiments proved the device correctness of operation. Having these done, the self-locking moving device data sheet was prepared. Taking into account the fact that according to The Machinery Directive, Directive 2006/42/EC the self-locking moving device is a machine, it was necessary to perform technical risk assessment. Summarizing up, thanks to performed design optimisation, it was possible to raise the safety level of the device operation, increase the device moving speed and to decrease the overall production costs by simplifying the device design.

1. Introduction

Optimisation is the science realm which deals in methods of the optimal solution selection for almost every area of human activity, e.g. technical, economical, financial etc. The design optimisation deals with problems both the geometrical shape selection and design mechanical features selection. This selection consists in determination of the optimal problem solution taking into consideration formerly given criterion or the criterion set. By the optimisation criterion the basic relations which lead to determination of the unknown design shape features are meant [1,2,3,4].

The optimisation is an action for which the main goal is to obtain the best possible results for given conditions and given objective function. Hence, the best result in the results set is called the optimal solution. The optimisation process gives lots of benefits for enterprise and people who perform it. Benefits of the optimisation process are as follows: increased financial profits, decreased recourses consumption, improved product operation, raised labour efficiency, reliability and safety improvement. Multi-criteria optimization is the most often used optimisation method during a process.
of the product design. This method is based on a systematic analysis of the problem. The designer most often has to solve the problem in which the product is designed in order to meet several conflicting criteria. The whole design process can be treated as a decision-making process, where it is necessary to choose the best solution [5,6].

In the design process, the designer should take into account the following assumptions: (i) the designer has the opportunity to choose a construction solution from an permissible set of solutions, (ii) the designer has at his disposal a system of values created by themselves or imposed in advance that allows him to evaluate solutions, (iii) the designer can decide and determine which of the available solution is the best, (iv) the designer can defend and justify his choice, which according to them is the most optimal. The above assumptions are called the problem of optimal choice (PoOC). It consists in, that the established system of values, assumptions for the project, allows specifying the criteria for assessing the solution. In such a way, this problem becomes a multi-criteria choice problem (MCCP). The solution to this problem requires determining a set of permissible solutions and a set of these assessments. The multi-criteria optimization task requires the definition of a vector objective function, by means of which a set of acceptable solutions will be mapped into a set of assessments. If the objective function is scalar, then we can talk about scalar optimization. Figure 1 shows the structure of the optimization problem.

The proceeding methodology in the process of optimal design of products is subordinated to practical reasons, aimed at obtaining specific solutions [10,11,12]. Assuming that the optimization criteria were defined during the design process, activities aimed at obtaining the optimal solution should include the following actions: (i) normalization of partial goal functions, (ii) scalarization of the normalized objective function using the weighting factors, (iii) defining a set of compromise solutions, (iv) defining a set of preferred solutions, (v) designation of a subset of preferred solutions from the set of compromise solutions, (vi) making the decision in order to choose the best optimal solution from the set of preferred solutions, based on the preferences of the decision-maker. Figure 2 shows stages of the multi-criteria optimisation process [1,8,9].

![Figure 1. The structure of optimisation problems.](image-url)
2. Optimisation of the self-locking moving device

The need of the design optimisation of the self-locking moving device appeared as a result of the operation information obtained in the feedback loop. The main remarks reported by the device servicing personnel were comments regarding the level of service safety and the need to increase the device moving speed. On this basis, it was found that it is necessary to carry out changes in the device design resulting from postulates reported by servicing personnel, also included a postulate to reduce manufacturing costs. Figure 3 shows the design of the self-locking moving device 20-101 type before introducing of the design changes.

The self-braking moving device type 20-101, as a drive unit, is intended for moving a train – a transport set with a load, e.g. a train with electrical equipment, dedusting devices, cooling devices and
other machines and devices along with the progression of the mine face (heading or wall) on tracks of underslung creepers with profile I 155, I 140E or I 140V. In this case self-locking device is located in the front of the transported set. Due to the walking cylinder used, the maximum pulling and pushing force for the 20-101 type device is 60 (kN). The self-locking moving device type 20-101 can be used both in underground mining plants in non-methane or methane fields. The self-locking moving device features the following technical data: Technical data for self-locking type 20-101:

- overall dimensions (length, width, height) – 1450x550x400 (mm),
- weight – 350 (kg),
- pulling or pushing forces up to 60 (kN),
- displacement speed in range of 40-70 (m/h),
- rail profiles I 155, I 140E, and 140V,
- maximum heading slop 27 (°).

The main components of the device are the plier barriers: right plier barrier (item 1, figure 3) and left plier barrier (item 2). The position of the proximity valve and the valve follower, thanks to which the device performs its work, determines whether the barrier is a left or a right one (item 3). The next element of self-locking moving device type 20-101 is the control block (item 4), consisting of two controllers connected to each other. The complete control block consists of the control block I (item 4a) and the control block II (item 4b). The whole device is completed by hydraulic cylinders; one is a walking cylinder with a pulling force not exceeding 60 (kN) (item 5), which is responsible for moving the entire transport set. The actuator connects both plier barriers with the use of pins in the ball joints. The other elements are actuators spreading the tick barrier (item 6, figure 3), which are built into the arms of the tick barriers.

2.1. Prototype of the self-locking moving device as a result of the optimization process

As a result of the optimization of the self-locking moving device type 20-101 design, a prototype design of a new device named 20-102 was developed. As a part of optimization process of the basic device design a new design of the plier barrier was developed and the device control system was changed. The introduced design changes have positively influenced the increase of the safety level of the device usage and the reduction of the manufacturing costs. In addition, as part of the modification process, the previously used walking cylinder was replaced with a new one, which resulted in improved parameters of the device movement. The last change introduced to the base design was a change consisting in the replacing of the type of the proximity valve formerly used. It allowed for further reduction of the manufacturing costs of the entire device.

2.1.1. The idea of the plier barrier arms design modifications

During the optimization processes of the self-locking moving design, the design of the straight and bend arm of the plier barrier have been modified. Figures 4 and 5 shows the modified designs of the straight and bend arm. The straight arm of the plier barrier consists of the following elements arm plate (item 1, figure 4), to which the braking blocks are welded (item 2). The braking block is responsible for blocking the barrier on the rail when the entire transport set is stopped. In the computer model, the block position was defined approximately according to a designer knowledge. It is because the spacing of the braking blocks with braking pads (item 3) attached to them is set individually for each case during the final device assembly because of the fact that the single plier barrier elements are manufactured with different deviations of dimensions. In addition, the correct spacing of these elements allows obtaining of the proper values of the pushing force and pulling force, which should amount to 60 (kN). The next elements of the straight arm are sleeves made of steel (item 4). Like braking blocks, sleeves are welded to the arm plate. The main role of the sleeves is to reinforce of the barrier structure in places of high load. The high load of sleeves results from fact that in these holes the connection bolts of the actuator are mounted or the first element of the transport set is fixed. The last part of the barrier – the sliding sleeve is mounted in the main hole (item 5). The sliding sleeve facilitates the rotation of the barrier against the main pin. The introduction to the design of the second
arm of the bent feature allows the freedom of the barrier opening, thus preventing the collisions of the arms during operation.

![Figure 4. The straight arm of the plier barrier.](image1)

![Figure 5. The bend arm of the plier barrier.](image2)

Figure 6 shows the 3D models of the plier barrier assembly and the self-locking type 20-102 moving device that were made in Autodesk Inventor 2016.

![Figure 6. Models of plier barrier and the self-locking type 20-102 moving device.](image3)

2.1.2. The plier barrier checking calculations
Having the 3D model of the plier barrier done, check calculations were made in order to determine whether the modified barrier structure would transfer the declared pulling and pushing forces that
amount to 60 (kN). These barrier elements were subjected to verification, which directly cooperate with elements of the transport set - the ones most loaded during the movement of the set. Figure 7 shows the calculation scheme set for checking calculations.

![Calculation scheme set for checking calculations of the plier barrier.](image)

Figure 7. The calculation schema set for checking calculations of the plier barrier.

Calculations were made for the following input data:
- the load of the pin's seat, \( P = 60 \) (kN)
- the diameter of the hole for the pin Ø30, \( d = 32 \) (mm)
- the thickness of the body plate, \( g = (30 + 20) = 50 \) (mm)
- the pin’s loaded surface, \( F = 2 \cdot (d \cdot g) = 3200 \) (mm2)
- surface thrust for steel S355J2, \( p_{dop} = 0.5 \cdot Re = 177.5 \) (MPa)
- computational strength, \( p_{ob} = \frac{p_{dop}}{4} = 44.4 \) (MPa).

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P = \frac{P}{F} < p_{ob} \quad \frac{60000}{3200} = 18.8 \text{ (MPa)} < p_{ob}
\]  

The connection elements of the plier barrier have a safety factor of 4 in relation to their immediate strength, corresponding to the existing type of stress. The remaining elements of plier barrier were not subjected to calculations, because their strength was tested experimentally during device tests. The test report has been described in the next section.

2.1.3. Mechanical load test of the plier barrier

On the basis of the model made in the Autodesk Inventor program, a prototype of the plier barrier was made. Next the device prototype was subjected to a mechanical load test taking into consideration the value of the safety factor. Mechanical load test of the self-locking moving device type 20-102 was aimed at checking the resistance and efficiency of the barrier's braking force at a load of 180 (kN). The test load was 3 times bigger then the working load occurring in the normal operation of the device type 20-102. The test was carried out without equipping the plier barrier with elements of power hydraulics. In this way, it was checked whether the geometry and kinematics of the self-locking type 20-102 device would guarantee the assumed braking force even in the case of failure of the power hydraulics. The hydraulic cylinder mounted in the plier barrier supports the braking process. Hence, it can be assumed that the plier barrier provides at least the same braking force as the barrier without power hydraulics.

In order to make load mechanical test the test stand which imitates underslung creeper was built. Figure 8 shows a view of the test stand. The test stand is made of 1 140V rail (item 1, figure 8) which was welded to the frame (item 2). The actuator (item 3) is attached to the ear (item 4), that was welded
to the rail, and also to trolley (item 5) and the force measuring system (item 6). The actuator was
mounted to the rail ear and also to the carriage in order to keep it in a horizontal position and to ensure
proper transmission of the load by plier barrier. The actuator is controlled by means of a hydraulic
distributor with valves that control working pressure (item 7). Thanks to controlling the working
pressure, it was possible smoothly control the load value of the plier barrier.

Figure 8. Figure with short caption (caption centred).

Figure 9 shows the measured course of the force loading the plier barrier achieved during
mechanical load test.

Figure 9. Distribution of the force loading the plier barrier.
As a result of the test, it was found that the achieved value of the plier barrier load exceeded the assumed value of 180 (kN) reaching a maximum value of 185.15 (kN). Moreover, it was found that the plier barrier was not moved in a direction parallel to the rail which confirms the correct operation of the barrier. The loading of the barrier with the force amounted to 180 (kN) load led to a reduction of the distance between the barrier's arms which is a normal phenomenon during the braking of the barrier, resulting in increased resistance and braking certainty. Table 1 shows the change in the distance between the barrier's arms at the actuator mounting location and the change of the distance between the axes of the braking pads as a result of the applied force.

Table 1. The distance change as a result of the mechanical load test.

| Measurement location | **Distance before the test (mm)** | **Distance after the test (mm)** | **The way of measurement** |
|----------------------|----------------------------------|---------------------------------|---------------------------|
| Distance between the barrier's arms at the actuator mounting location | 410 | 380 | |
| Distance between the braking pads axes | 240 | 210 | |

On the basis of the assessment, it was found that as a result of the test the plier barrier was not destroyed, and using the proper tools it was possible to unlock it and release the barrier from the rail. Summarizing up, the plier barrier of self-locking moving device ensures safe and reliable braking with 180 (kN) force, which is 3 times the maximum load applied to the barrier during normal service. The plier barrier type 20 - 102 self-locking moving device features right mechanical resistance ensuring safety during 3 times its overload.

2.1.4. Test of the self-locking moving device 20-102 type

Having the mechanical load tests of the plier barrier carried out, movement tests of the whole device were carried out with a measuring bench that imitates the track of the underslung creeper. Tests of the self-locking type 20-102 moving device and its individual design elements were performed on a track made of I 140V rails. Figure 10 shows the self-locking type 20-102 moving device installed on the measuring bench. The device consists of two plier barriers. Each barrier features expanding hydraulic cylinder that is connected to its arm' ends. There is a walking hydraulic cylinder installed between the barriers. The walking cylinder allows the device to be moved. A hydraulic control unit controls the work of the device. The hydraulic energy was generated by a separate hydraulic power unit. The hydraulic fluid of the HLP-46 type was used as the working fluid. The hydraulic unit parameters were as follows: flow rate Q = 10 (dm$^3$ min$^{-1}$), pressure p = 24.0 (MPa). The following tests were carried out during the device movement tests: (i) operation test at rest, (ii) studying of the free walking of the device on rails, (iii) test of walking function, braking ability at inclination and load, (iv) operation and
safety test of the control unit, (v) Safety test during moving the device on the rail track, (vi) test of an unintended opening of the braking device.

Figure 10. The self-locking type 20-102 moving device installed on the measuring bench.

During the operation at rest the following tests were performed: (i) accordance of the dimensions of the individual components of the device with the technical documentation were checked, (ii) the correctness of hydraulic connections was checked, (iii) bolted joints, bolts together with the retaining rings were complete, in the required amount and were properly installed, (iv) the maximum pulling force in both walking directions was limited to the value of 60 (kN). The device passed all the tests without any remarks. The device free walking tests showed that the self-locking moving device worked properly on the track arranged in a straight line for the permissible deviations of the rails from straightness horizontally and vertically. The walking of the device was smooth. The transfer and taking of the loading force by the plier barriers was carried out without striking. There were no occurrences that could lead to overloading of the device and rails. The average walking speed obtained from three tests was $v = 0.8$ (m min$^{-1}$). Walking on a horizontal curve with a radius of 4 (m), the test was not performed. It was unnecessary, the device of such dimensions moves freely on such curve. During the test of walking function, braking ability at inclination and load: (i) the behavior of the device type 20-102 was checked on the basis of tests, which consisted in loading the device in the longitudinal direction with a pulling force of 60 (kN) that was obtained by an external actuator. The tests were performed both for pushing and pulling force. (ii) The braking function was maintained for 15 (s). Based on the conducted tests, the following was found: (i) the leakage loss in the walking cylinder and in the actuators controlling the plier barriers were not present, (ii) the tests carried out for both walking directions showed that the device works properly. Carrying out tests of operation and safety test of the control unit involved: (i) checking of the operation of the control unit for both walking directions. The performed tests show that the device works properly for both walking directions. (ii) Safety test in case of power failure. During the walking tests, the loss of energy was simulated by switching off the hydraulic power unit or closing the shut-off valve that is located between the power unit and device. In case of a power failure, one of the plier barriers remains closed. Releasing of the control lever causes that the spring automatically returns to the zero position due to the spring force. Opening of the plier barrier is impossible, due to the presence of the minimum pressure valve, until the hydraulic energy not return. (iii) Safety test in case of insufficient hydraulic energy (too small or strongly fluctuating working pressure). If the hydraulic energy of the source is
insufficient (too small operating pressure), the control is not possible, because the minimum pressure valve at the power supply side remains closed. The minimum pressure is set to 8 (MPa). Shifting of the control lever of the second actuator controller will not cause any effects. In the case of a pressure drop when the plier barrier is already opened, the walking is stopped because the minimum pressure valve in the hydraulic control unit stops the energy flow to the walking cylinder. On the other hand, it would appear that with a strongly fluctuating pressure and a displaced start lever, one of the plier barriers will be continuously opening and closing. In both cases, however, the second plier barrier will remain permanently closed. Switching with the possibly partially opened tick grip is impossible as above. Releasing the control brings the control lever immediately to the zero position. Safety test in case of hydraulic hose bursting; it was tested whether the loss of energy due to the bursting of hydraulic hoses could unintentionally open the plier barriers or the unintentional movement of the walking cylinder. The bursting of the hydraulic hoses was simulated by opening a suitable valve in the hydraulic system. The following cases were tested: (i) bursting of the hose used to close the plier barriers. Bursting of the hose used to close the plier barriers in case the hose is loaded with full pressure will cause that the minimum pressure valve will turned off the starter lever function due to pressure loss and prevent its switching. (ii) Bursting of the hose used to open the plier barriers. Bursting of the hose used to open the plier barrier in case the hose is powered causes that the opening process is stopped. The resulting pressure drop will cause the minimum pressure valve to switch off the starter lever function and prevent any switching. In both cases; it is (i) and (ii) the plier barriers remained closed. (iii) Safety test in case of incorrect connection of hydraulic hoses. The actuators controlling the plier barriers are supplied with hydraulic hoses of various diameters. The actuator piston side (blocking of the barrier) is powered by a DN12 hose, while the actuator rod side (unblocking of the barrier) with a DN10 hose. Hence, incorrect connection of hoses to the barrier actuators could lead to the simultaneous opening of both barriers. Like for actuators controlling the plier barriers, both sides of the walking actuator are powered with the two different dimensions hoses DN10 and DN12 respectively. There are the two overflow valves in the control unit. These valves are used to limit the working pressure for each side of walking. Incorrect connection of hoses to the walking actuator could cause to unplanned rise of the working pressure because of the different diameters of piston and rod side of actuator – different piston and rod forces. In order to reduce the risk of incorrect device operation all hydraulic hoses used and their connection points should be permanently and unambiguously described. (iv) Safety test in case of oil embolism in the inlet hose. In the control unit of the self-locking type 20-102 moving device, in the run-off part, an overflow valve is installed, set at 0.8 MPa. In the case of a oil embolism in the return flow, this valve will open and the operating fluid flows out, out of the hydraulic system. The pressure in the run-off hose can reach a maximum of 0.8 MPa, an unintentional opening of the plier barrier is therefore impossible. There were not installed any hydraulic components in the device that store pressure energy that could cause unintentional opening of the braking device.

3. Conclusion
Computer-aided design and modelling facilitates the design process of machine and equipment components. The use of CAD programs allows shortening the design process and reducing project costs. This is a very important advantage, because nowadays, the time from the start of design to the production of the finished element should be as short as possible. Shown in the paper the optimisation process was made taking into account the criteria of safety improvement, device manufacturing cost and technical parameters. The basis for the optimisation process was self-clamping type 20-101 moving device. During the optimization of the device design, information acquired from the device users as well as information obtained during direct observation of the device operation in the work environment was used. As a result of the device design optimisation the following changes to its design were introduced: (i) due to the nature of the work (highly suspended rails) changes in the control of the device were made, the usual hydraulic ones were changed into a multi-band, which significantly affects the user's safety. Thanks to such a solution, the person operating the machine
controls the device at a safe distance from the conveyor belt. (ii) Thanks to the use of a higher stroke actuator, a higher travel speed was achieved. The design changes introduced into the initial design, such as the change in the shape of the bend, the introduction of sliding sleeves instead of the plates, the smaller number of welds necessary to do, the change of the proximity valve terminal and the change of the valve type positively influenced the production costs. The self-locking type 20-102 moving device was allowed to sale as result of its acceptance by State Mining Authority in Katowice, Poland. The first sold device works in hard coal main “Chwałowice”. On the basis of information acquired from mine employees, it was found that the process of optimizing of the basic device design was successful.

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