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Software Environment for Computer-Aided Heuristic Optimization of Hydraulic Systems for Synchronous Movement of Actuators of Various Functional Purposes

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Abstract. A software environment was developed for computer-aided design of optimal throttle hydraulic synchronization systems of actuators of various functional purposes operating under conditions of external alternating-sign force effects. The criterion of an optimization procedure was the minimization of a mismatch time of relative movement of actuators during operation. A compute core of an object-oriented code was constructed on the basis of a dynamic mathematical model of a synchronization system consisting of four power cylinders. A model problem was solved with the help of the created software environment. This model problem demonstrated the efficiency of the proposed multidimensional optimization process. The methodology was based on the use of the well-known heuristic method (binary coded genetic algorithm) and the subsequent improvement (in the sense of a given objective functional) of the obtained solution by a method on the basis of the Hooke-Jeeves algorithm. Recommendations on the practical application of the software and mathematical support for achieving the best convergence to the extreme value of a vector of controlled parameters were formulated.

1. Introduction

This article is a logical extension and further development of applied researches; these researches were described in [1]. The essence of the problem lies in the practical application of optimization methods and, in particular, modern heuristic algorithms for searching extreme values of controlled parameters during solving problems of synchronizing the movement of actuators of hydraulic systems [2–5]. Taking into account difficulties in the implementation of many optimization algorithms and in order to save a computer time, a throttle method of synchronizing the actuator was chosen to demonstrate the efficiency of the optimization procedure. A hydraulic scheme of the corresponding synchronization system including four power cylinders (PC^k) and throttles with effective areas $(\mu f)^k$ ($\mu -$ flow rate coefficient, $f -$ throttle section area), $k=\overline{1,4}$ is shown in Figure 1.

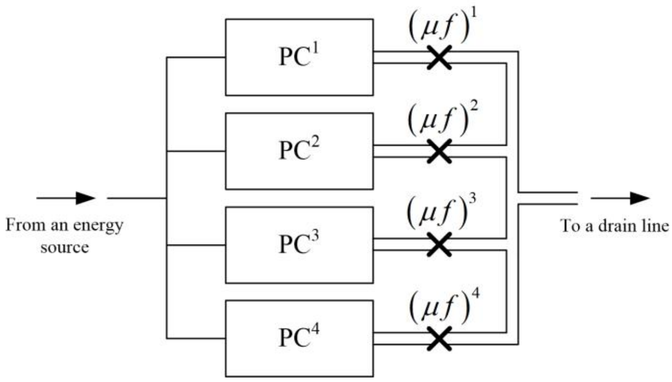

Figure 1. Hydraulic scheme of the synchronization system with four power cylinders.

Results of this research are supposed to be distributed to various hydraulic synchronization systems, for example, the systems built on the basis of flow stabilizers. However, in this case, it is necessary to perform a non-stationary computer analysis of the internal hydrodynamic processes using three-dimensional finite-volume modeling systems [6–8] for each iteration of solving the direct task. This fact greatly complicates the creation of the corresponding software tools.

2. Mathematical model of the throttle synchronization system of direct task

The dynamic model of this synchronization system is represented by the equations $\left(k=\overline{1,4}\right)$:

$$d^2\beta^k/dt^2=\left(\left(p_{ES}-p^k_{liq}\right)S^kF^k_{1\pm}\left(\beta^k\right)-r^k_{vfric}\left(F^k_{1\pm}\left(\beta^k\right)\right)^2\omega^k-R^k_{\pm}\left(\beta^k\right)\left(\omega^k\right)^2+M^k_{ext}\right)\Big/J^k_{red}\,, \quad (1)$$

$$dp^k_{liq}/dt=\left(a^2/V^k_{liq}\right)\left(\rho^k_{liq}S^kF^k_{1\pm}\left(\beta^k\right)\omega^k+\mathrm{sgn}\left(p^k_{liq}-p_{out}\right)\mu^kf^k\left(2\rho^k_{liq}\left|p^k_{liq}-p_{out}\right|\right)^{0,5}\right). \quad (2)$$

Designations of physical quantities included in the system (1)–(2) are given in [1].

3. Multidimensional optimization problem

3.1. Objective function of the optimization problem

The mapping $\Phi: Dr^1\times Dr^2\times Dr^3\times Dr^4\to\mathbb{R}_+$ is considered, for which

$$\Phi\left(M^1,M^2,M^3,M^4\right)=\max\left\{t^1,t^2,t^3,t^4\right\}-\min\left\{t^1,t^2,t^3,t^4\right\}\to\min\,. \quad (3)$$

The function of four variables Φ is called the objective function (target function) for the multidimensional optimization problem; this function is defined on the set $Dr^1\times Dr^2\times Dr^3\times Dr^4\subset\mathbb{R}^4$ in such way that

$$M^k=\left(\mu f\right)^k\in Dr^k\subset\mathbb{R}^1,\ k=\overline{1,4}\,, \quad (4)$$

where $Dr^k=\left[\left(\mu f\right)^k_{\inf};\left(\mu f\right)^k_{\sup}\right], \left(\mu f\right)^k_{\inf}, \left(\mu f\right)^k_{\sup}\in\left\{\mathbb{R}:\left(\mu f\right)^k_{\inf},\left(\mu f\right)^k_{\sup}>0,\ \left(\mu f\right)^k_{\inf},\left(\mu f\right)^k_{\sup}<+\infty\right\}$, $\left(\mu f\right)^k_{\inf}$, $\left(\mu f\right)^k_{\sup}-$ boundaries of ranges of variation of the effective area of the k-th throttle, t^k- time of movement of Actuator^k, $k=\overline{1,4}$; this time is determined by solving the direct task. The problem of minimization of a time of relative movement for four actuators of the throttle synchronization system includes the function (3) and restrictions (4) to effective areas of throttles $(\mu f)^1$, $(\mu f)^2$, $(\mu f)^3$, $(\mu f)^4$.

3.2. Heuristic algorithm of the global optimization

The theory of optimization methods in the development of global extremum search problems offers original ways to decompose a multidimensional region of a space of controlled parameters [9], program codes for efficient setting of computational optimization algorithms [10], various heuristic methods [11–13]. An evolutionary algorithm with a modification was used to calculate the global extremum of the function Φ on the set $Dr^1 \times Dr^2 \times Dr^3 \times Dr^4 \subset \mathbb{R}^4$. This algorithm implemented a procedure of positional binary coding, a combination of rank proportional selection and a roulette principle; a single-point crossover was selected as an individual crossing operation, an inversion principle was applied instead of a mutation operator. In relation to the problem (3)–(4), a chromosome consisting of four genes $M^k \in Dr^k$, $k = \overline{1,4}$ is a set of parameters $(\mu f)^1$, $(\mu f)^2$, $(\mu f)^3$, $(\mu f)^4$. The meaning of the adjusting procedure based on the classical direct search Hooke-Jeeves algorithm with a constant acceleration factor [14, 15] for calculating the global optimum is described in the work [1].

4. Software environment of the heuristic optimization

4.1. Design of the compute core

The fourth-order classical numerical finite-difference Runge-Kutta method and the Runge-Kutta-Merson method with the evaluation of the solution error for each variable integration step were used for obtaining a discrete analog of continual equations of the mathematical model (1)–(2). The compute core has a flexible architecture so that it is possible to quickly make modifications to individual blocks of the code and further expand its functionality. Figure 2 shows a diagram of classes of the software environment; identifiers of the classes reflect the meaning of algorithmic operations performed by them.

The classes-interfaces, which are ICauchyProblemSode (defines the specification of classes oriented to solve the Cauchy problem for a system of ordinary differential equations) and IOptimizationProblem (determines the specification of classes oriented to solve the multidimensional optimization problem) are parameters of the IFdmSode::solve() and IOptimizationMethod::solve() methods belonging to the classes-interfaces, which are IFdmSode (defines the specification of classes oriented to the algorithmization of finite-difference methods) and IOptimizationMethod (determines the specification of classes oriented to the algorithmization of optimization methods), respectively. The RungeKuttaMerson and RungeKutta4 classes are descendants of IFdmSode. These classes implement the corresponding numerical algorithms for solving the direct task. The BGA and HookeJeeves classes are descendants of IOptimizationMethod. These classes implement the binary coded genetic algorithm and the Hooke-Jeeves method, respectively. The DirectSynchronizationProblem (implements the ICauchyProblemSode interface) and OptimizationSynchronizationProblem (implements the IOptimizationProblem interface) classes contain programming constructs for formalizing right-hand sides of differential equations and the initial conditions of the direct task and objective function of the optimization problem (3)-(4), respectively. The OptimizationSynchronizationProblem class aggregates the DirectSynchronizationProblem class and the IFdmSode class-interface, since it is necessary to repeatedly solve the direct task to determine values of the objective function (3).

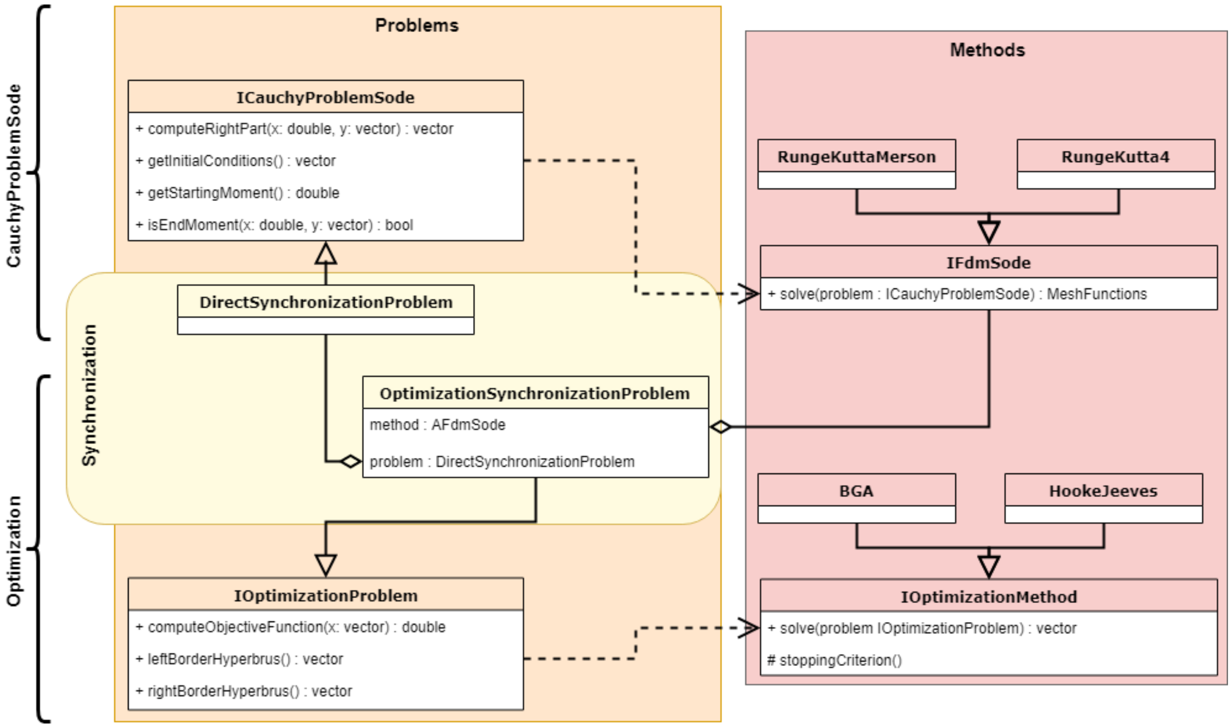

Figure 2. Diagram of classes of the software environment.

Key features of the developed class hierarchy should be noted:

- providing the modular debugging of the used numerical methods (the introduction of random errors in other logical elements of the code is excluded due to a high degree of data encapsulation);
- testing numerical methods for a wide class of applied problems with any number of unknown functions (features of the formulation of the test problem are described in a special service area);
- providing the continuity of well-established numerical methods by other application programs (using dll-library tools);
- adding new numerical methods to the compute core occurs without changing a stable functioning algorithmic structure of the software environment due to the use of the concept of data polymorphism;
- using a combination of various finite-difference and computational optimization algorithms during solving the direct task and in the process of searching a global extremum of the objective function.

4.2. User interface structure

The window interface of the software environment contains four tabs. The [Synchronization system] tab provides the access to input fields of geometric and mass characteristics of power cylinders (PC^k), $k=\overline{1,4}$, physical parameters of an energy source and a working fluid, as well as the values of external force impacts applied to Actuators^k, $k=\overline{1,4}$. Applying the tools of the [Direct task] tab, the user can perform a computational experiment using the input data defined in the [Synchronization system] tab, as well as get a graphic visualization of results. The [Optimization problem] tab is intended for solving the formulated optimization problem (3)–(4). The process and results of the optimization are presented in a convenient numerical and graphical form. The [Settings of the numerical methods] tab contains dialog elements that determine the efficiency of functioning numerical algorithms and parameters of saving the results of calculations in the form of text files. The command of the Language menu allows changing the interface language from Russian to English and vice versa.

5. Research results

The model problem of selecting the optimal effective areas of throttles was solved with the help of the developed computer-aided design environment. The following input data ([Synchronization system] tab) were selected to simulate the operation of the synchronization system. It was accepted that constant external force impacts were given for actuators of the corresponding power cylinders: $M^1_{ext} = 900\ \mathrm{N \cdot m}$ (applied to Actuator[1]), $M^2_{ext} = 600\ \mathrm{N \cdot m}$ (applied to Actuator[2]), $M^3_{ext} = 0$ (applied to Actuator[3]), $M^4_{ext} = -600\ \mathrm{N \cdot m}$ (applied to Actuator[4]); the pressure of gases from the energy source was assumed constant and equal to 10.13 MPa; $(\mu f)^k_{\inf} = 44.5\ \mathrm{mm}^2$, $(\mu f)^k_{\sup} = 76.5\ \mathrm{mm}^2$ that corresponded to diameters of $d^k_{\inf} \approx 8.7\ \mathrm{mm}$, $d^k_{\sup} \approx 11.4\ \mathrm{mm}$ for $\mu^k = 0.75$, $k = \overline{1,4}$.

The following setting values of the genetic algorithm were chosen ([Settings of the numerical methods] tab): the population size was limited to 16 individuals, the gene length was 32 bits; the number of parental pairs in the population was 4. This meant that 16 individuals were processed for each iteration of optimization transformations; wherein the certain controlled parameters $(\mu f)^1$, $(\mu f)^2$, $(\mu f)^3$, $(\mu f)^4$ or points $(M^1, M^2, M^3, M^4) \in Dr^1 \times Dr^2 \times Dr^3 \times Dr^4$ corresponded to them. The empirical value of the mutation (inversion) probability of individuals was equal to 0.1; the number of iterations of the binary coded genetic algorithm was 10. Furthermore, the step increase factor of the Hooke-Jeeves algorithm was 1; and the step division factor was equal to 2.

The following results are displayed after pressing the [Run the computational experiment] button. Figure 3 shows graphic dependences of the angular displacement of four actuators from time ([Direct task] tab, select [Angular displacement of the actuator] in the drop-down list).

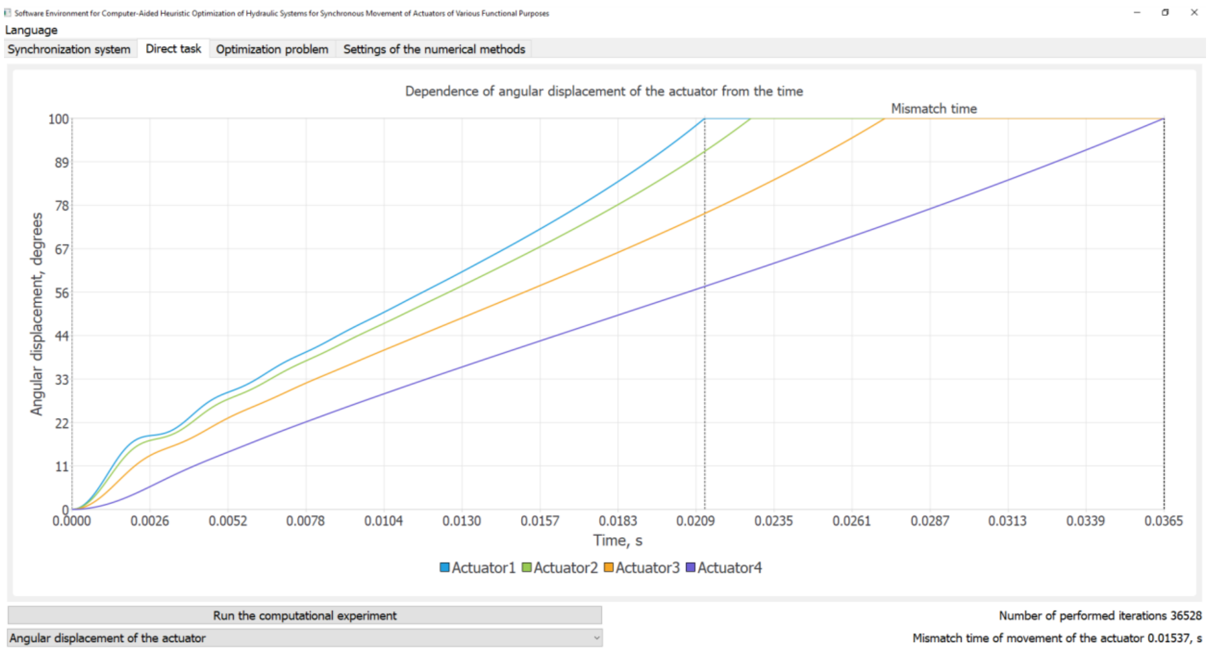

Figure 3. Graphic illustration of the result of solving the direct task (graphs of angular displacement of Actuator[1], Actuator[2], Actuator[3], and Actuator[4]).

Figure 4 shows dynamic curves showing an oscillatory nature of the change in the projection of the angular velocity vector of each actuator in time ([Direct task] tab, select [Angular velocity of the actuator] in the drop-down list). The case of non-synchronous movement of four actuators was shown for values of effective diameters of throttles equal to $(\mu f)_0^k = 60\ \mathrm{mm}^2$ for $\mu^k = 0.75$, $k = \overline{1,4}$. The difference in the time of reaching the limiting values $\beta_{\max}^k = 100^\circ$ (value of the function Φ) by angular coordinates β^k, $k = \overline{1,4}$ was $\Phi_0 = 15.37 \cdot 10^{-3}$ s for 36528 executed iterations of the finite-difference method (value of the integration step was 10^{-6} s). Since an external moment M_{ext}^1, $M_{ext}^1 > M_{ext}^2 > M_{ext}^3 > M_{ext}^4$ having a positive sign and contributing to a faster change in its angular coordinate β^1 is given for Actuator[1], and an external moment M_{ext}^4 having a negative sign and slowing its dynamics is given for Actuator[4], then Actuator[1] reaches the end point of its rotational motion earlier than Actuator[2], Actuator[3], Actuator[4], and the time difference Φ_0 occurs.

Figure 5 shows dynamic curves describing changes in the angular coordinate of each actuator in time after performing the optimization procedure for minimizing the mismatch time of movement of four actuators of the considered pneumohydraulic synchronization system ([Optimization problem] tab, select [Angular displacement of the actuator (after optimization)] in the drop-down list).

As a result of the sequential application of the genetic algorithm and the Hooke-Jeeves method ([Optimization Problem] tab, sequential pressing of the [Start solving the optimization problem by the BGA] and [Continue solving the optimization problem by the HJ] buttons), this time difference can be minimized: $\Phi_{\min} = 3.125 \cdot 10^{-5}$ s; extreme parameters of the throttles are equal to $(\mu f)_{\min}^1 \approx 48.58\ \mathrm{mm}^2$, $(\mu f)_{\min}^2 \approx 47.84\ \mathrm{mm}^2$, $(\mu f)_{\min}^3 \approx 56.06\ \mathrm{mm}^2$, and $(\mu f)_{\min}^4 \approx 76.5\ \mathrm{mm}^2$ that corresponds to diameters $d_{\min}^1 \approx 9.08$ mm, $d_{\min}^2 \approx 9.01$ mm, $d_{\min}^3 \approx 9.76$ mm, and $d_{\min}^4 \approx 11.4$ mm for $\mu^k = 0.75$, $k = \overline{1,4}$.

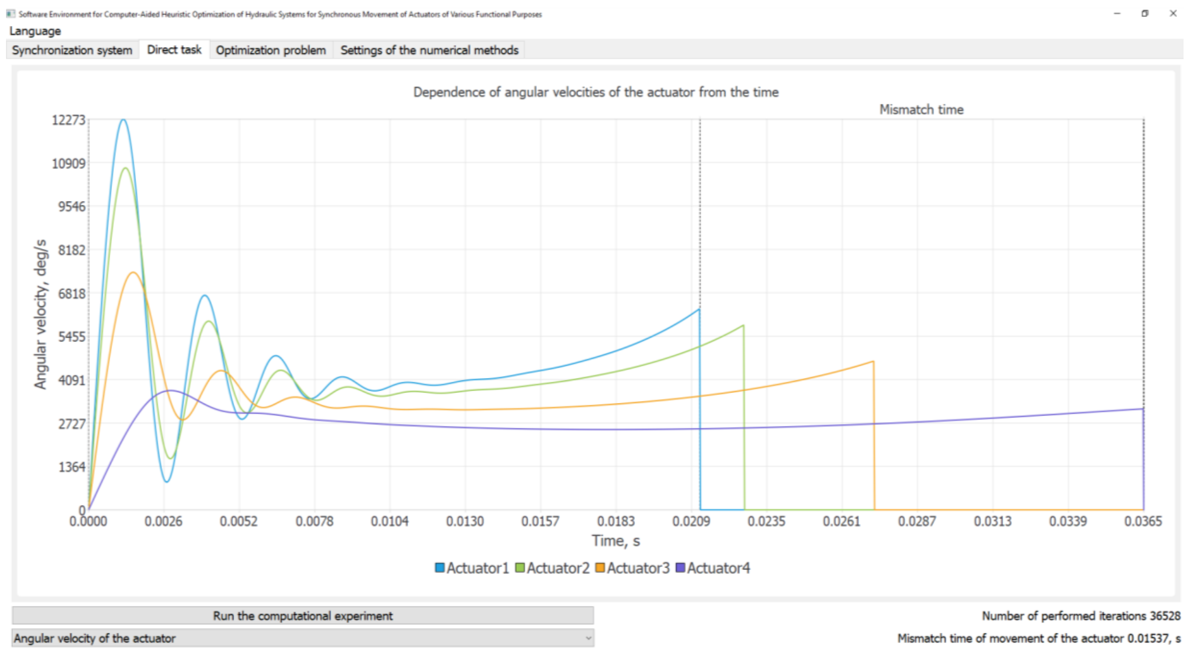

Figure 4. Change in the projection of the angular velocity vector of each actuator in time.

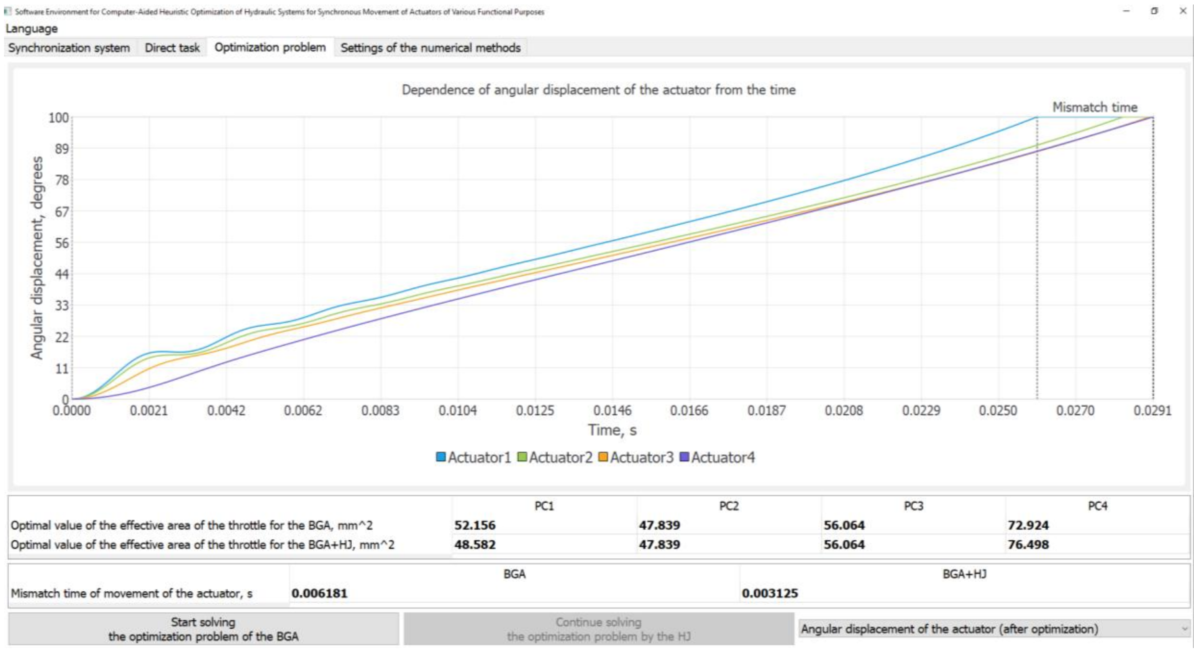

Figure 5. Graphic illustration of the result of the optimization process.

Figure 6 shows the graphic dependence of the value of the objective function from the iteration process ([Optimization problem] tab, select [Graph of the target function] in the drop-down list) after specifying extreme values of the function Φ by the Hooke-Jeeves method. The efficiency of the joint use of two optimization methods was confirmed for searching for a global minimum of the function Φ, since the value of the objective function could be approximately reduced by half.

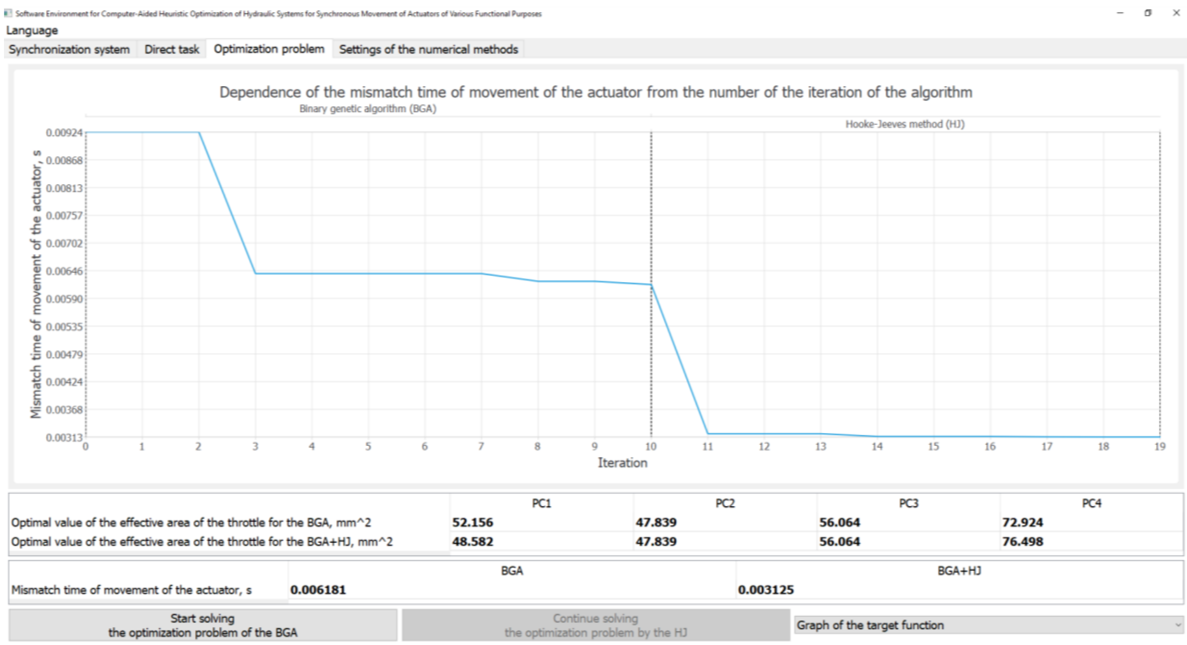

Figure 6. Dependence of the value of the objective function from the number of the iteration process.

6. Conclusions
A software environment was developed for optimal design of synchronization systems of parallel operating hydraulic drives of mechanical systems with the throttle control principle. The heuristic global optimization algorithm with the procedure for specifying the optimal solution was a base for the compute core of the software environment. The efficiency of such optimization procedure during searching the global minimum of the objective function was confirmed; the value of the objective function could be approximately reduced by half. The software environment allows providing the expansion in the direction of multi-criteria optimization; this environment can be used during designing other types of hydraulic synchronization systems.

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