UDC 62.82:62.85 **doi: 10.20998/2411-3441.2023.1.09**

N. FATIEIEVA, O. FATYEYEV, V. POLIAKOV

RELIABILITY OF HYDROPNEUMODRIVES FOR METAL CUTTING EQUIPMENT

The reliability of hydropneumodrives largely determines the safety of machine tools, metal cutting equipment, the movement of transport vehicles, and the flight of modern passenger aircraft, and their failures can in some cases lead to accidents. The design stage is crucial in ensuring reliability. The main tasks of reliability research and calculation at this stage can be divided into three groups. First, it is a justification of reliability requirements for the main elements of the hydraulic pneumatic actuator (the task of reliability norming). This task is solved at an early stage of design and involves the preliminary development of the unit structure and justification of design principles. Secondly, it is to ensure the reliability of the elements and the unit as a whole. This group of tasks includes research and quantitative assessment of the efficiency of possible ways to ensure reliability; selection of basic design characteristics, statistical reserves of durability and longevity, stability reserves and other indicators; comparative analysis of options and selection of optimal designs. Thirdly, these are control calculations of the unit's reliability according to the design documentation. Algorithms for the distribution of normalised reliability indices at the design stage for hydropneumodrives implemented by the standard positional structure method and the minimisation method are obtained. Algorithms allow already at the early stages of hydropneumodrive design to normalise reliability indices, which makes it possible to obtain optimal solutions of reliability issues at the subsequent stages of development of the drive life cycle. The methods of calculation and determination of design relations for finding quantitative characteristics of failure-free indices of designed hydropneumodrives, implemented by the method of standard positional structure and the method of minimisation, are selected, which allows designing highly reliable hydropneumodrives for new metal cutting equipment. Evaluation of reliability indicators of hydropneumodrives at the stage of preliminary design allows to make a rational choice of structural scheme and parameters, to select appropriate materials and elements of scheme realisations.

Keywords: reliability, hydropneumodrive, probability of failure-free operation, failure rate, method of distribution of reliability norms, vulnerability factor.

Н. М. ФАТЄЄВА, О. М. ФАТЄЄВ, В. В. ПОЛЯКОВ

НАДІЙНІСТЬ ГІДРОПНЕВМОПРИВОДІВ МЕТАЛОРІЗАЛЬНОГО УСТАТКУВАННЯ

Надійність гідропневмоприводів у великій мірі визначає безпеку роботи верстатів, металорізального устаткування, руху транспортних машин, польотів сучасних пасажирських літаків і їх відмови в ряді випадків можуть привести до аварій. Етап проектування є визначальним у забезпеченні надійності. Основні завдання дослідження і розрахунку надійності на цьому етапі умовно можна розділити на три групи. По-перше, обгрунтування вимог по надійності до основних елементів гідропневмоприводу (завдання нормування надійності). Це завдання вирішується на ранній стадії проектування і передбачає попередню розробку структури агрегату і обгрунтування принципів проектування. По-друге, забезпечення надійності елементів і агрегату в цілому. Ця група завдань включає дослідження і кількісну оцінку ефективності можливих способів забезпечення надійності; вибір основних проектних характеристик, статистичних запасів міцності і довговічності, запасів стійкості та інших показників; порівняльний аналіз варіантів і вибір оптимальних конструкцій. По-третє, контрольні розрахунки надійності агрегату за проектною документацією. Отримано алгоритми для розподілу нормованих показників надійності на етапі проектування для гідропневмоприводів, реалізованих методом стандартної позиційної структури і методом мінімізації. Алгоритми дозволяють вже на ранніх стадіях проектування гідропневмоприводів нормувати показники надійності, що дає можливість отримувати оптимальні рішення питань надійності на наступних етапах розробки життєвого циклу приводу. Обрано методи розрахунку і визначення розрахункових співвідношень для знаходження кількісних характеристик показників безвідмовності проектованих гідропневмоприводів, реалізованих методом стандартної позиційної структури і методом мінімізації, що дозволяє проектувати високонадійні гідропневмоприводи нового металорізального обладнання. Оцінка показників надійності гідропневмоприводів на етапі ескізного проектування дозволяє здійснити раціональний вибір конструктивної схеми і параметрів, підібрати відповідні матеріали і елементи реалізацій схем.

Ключові слова: надійність, гідропневмопривод, ймовірність безвідмовної роботи, інтенсивність відмов, метод розподілу норм надійності, коефіцієнт уразливості.

Introduction. In recent years, there has been a tendency to expand the scope of application of hydropneumodrives and increase the number of machines and equipment that are installed with hydropneumodevices, so the question of ensuring the reliability of hydraulic pneumatic drives and their elements has become especially important. Firstly, the reliability of hydropneumodrives largely determines the reliability of the entire machine or equipment, and the timely completion of a given amount of work often depends on the proper operation of hydropneumodrives. Failures of hydraulic pneumatic drives on mass-produced machines (machine tools, agricultural machines, tractors, etc.) lead to downtime and significant economic losses [1, 2]. Secondly, reliability of hydropneumodrives to a great extent determines the safety of machine tools, metal-cutting equipment, movement of transport machines, flights of modern passenger aircraft and their failures in some cases can lead to accidents [3]. Therefore, the questions within the competence of hydropneumodrive reliability science are still relevant today.

Problem statement in a general way. The analysis of earlier works connected with calculations of reliability of hydropneumodrives has shown that researches and the decision of a considerable part of questions arising in the reliability theory in relation to hydropneumodrives, only begun, and therefore in it many problems have not received the due decision. Recently, there has arisen the necessity of significant increase, in comparison with the existing ones, of reliability of new high-performance hydropneumodrives and insufficient development of theoretical bases and practical methods of their reliability analysis at the design stage [4, 5]. Operational and accurate analysis of reliability of hydropneumodrive elements allows to reasonably take progressive design and technological solutions to improve the reliability of elements, thus guaranteeing the optimal performance of the new design.

Thus, increasing reliability and improving and simplifying the process of selecting the best variant of hydropneumodrives of metal cutting equipment at the design stage by carrying out synthesis of schemes taking into account quantitative reliability indicators and distribution of normalised reliability indicators, is an actual scientific and practical problem.

Main part. The design stage is a determining one in reliability assurance. The main tasks of reliability research and calculation at this stage can be conditionally divided into three groups [6, 7]:

1) The first group is justification of reliability requirements to the main elements of hydropneumodrive (the task of reliability norming). This task is solved at the early stage of design and provides preliminary development of the drive structure and justification of design principles.

2) The second group is to ensure the reliability of elements and the drive as a whole. This group of tasks includes research and quantitative assessment of the effectiveness of possible ways to ensure reliability; selection of basic design characteristics, statistical reserves of durability and longevity, stability reserves and other indicators; comparative analysis of options and selection of optimal designs.

3) Control calculations of actuator reliability according to project documentation.

1. Algorithms for normalisation of reliability indices for hydropneumodrives implemented by the standard positional structure method and the minimisation method. Distribution of reliability norms is carried out at the stages of preliminary and detailed design of a technical system [8]. It is assumed that at any of these stages of design the system can be divided into a certain number of subsystems in the form of separate assemblies and proceed from the initial reliability of each subsystem, obtained by calculation or according to the results of tests of the subsystems [7]. Using methods of distribution of normalised reliability indices, it is possible to lay down the required functionality of the hydropneumodrive already at the design stage.

For hydropneumodrives, which are synthesised by the method of standard positional structure [9–11], the distribution of normalised reliability indices at the design stage is preferably carried out by two methods: the method of proportional distribution and the method of distribution of reliability requirements taking into account the relative vulnerability of elements [7, 8] and its algorithm is implemented as follows:

- decomposition – breaking down the original complex system into simple elements;
- for the command apparatus we apply the method of proportional distribution of reliability indices, since the command apparatus is considered as a system consisting of sequentially connected subsystems containing k_i elements;
- determine the quantitative composition of subsystems in the command apparatus: each subsystem consists of an AND element ($\wedge$), a memory element (ME) and an OR element ($\vee$), i.e. $k_i = 3$;
- determine the total number of subsystems of the command apparatus: n;
- set the required probability of failure-free operation $P^R(t)$;
- calculate the number of "reduced" elements:

$$\alpha_i = \frac{\sum_{l=1}^{n}\sum_{j=1}^{m} \lambda_j \cdot k_{lj}}{\sum_{j=1}^{m} \lambda_j \cdot k_{ij}};$$

- determine the required probability of failure-free operation of the subsystem of the command apparatus:

$$P_i = \sqrt[\alpha i]{P^R};$$

- determine the quantitative composition of the remaining elements: identify the basis and intermediate elements {the basis is a constant hardware part of the hydropneumodrive, which remains unchanged both at realisation of the scheme by the method of standard positional structure (SPS) and at realisation by the method of minimisation. The variable part of the hydropneumodrive are intermediate elements (IE), the number of which, in general, depends on the ways of realisation of logic functions};
- apply to the remaining elemental composition the method of distribution of reliability requirements taking into account the relative vulnerability of elements;
- calculate vulnerability coefficients:

$$\omega_j = \lambda_j \Big/ \left(\sum_{i=1}^{n} \lambda_i \right), \quad j = 1,2,...,n;$$

- determine the required failure rates of elements $\lambda_j^R = \omega_j \cdot \Lambda^R$, $j = 1, 2, ..., n$;
- find the necessary values of probability of failure-free operation of elements;
- check the correctness of normalisation of reliability indices of elements by calculating the total probability of failure-free operation of the hydropneumodrive:

$$P_{SPS}(t) = (P_{CA}^{sub})^n \cdot P_{Basis}(t) \cdot P_{IE}(t) = P^R(t),$$

if the hydropneumodrive doesn't contain any intermediate elements:

$$P_{SPS}(t) = (P_{CA}^{sub})^n \cdot P_{Basis}(t) = P^R(t).$$

For hydropneumodrives, which are synthesised by the minimisation method [9, 10], the distribution of normalised reliability indices at the design stage is preferably carried out by the method of distribution of reliability requirements taking into account the relative vulnerability of elements [7, 8] and its algorithm is implemented as follows:

- decomposition – break down the initial complex system into simple elements and consider the quantitative and elemental composition of the hydropneumodrive: identify the basis, intermediate elements and memory element – if they are provided by the scheme implementation;
- set the required probability of failure-free

operation $P^R(t)$;

- calculate vulnerability coefficients:

$$\omega_j = \lambda_j / \left(\sum_{i=1}^{n} \lambda_i \right), \quad j = 1,2,...,n ;$$

- determine the required failure rates of elements $\lambda_j^R = \omega_j \cdot \Lambda^R$, $j = 1, 2, ..., n$;

- find the necessary values of probability of failure-free operation of elements;

- check the correctness of normalisation of reliability indices of elements by calculating the total probability of failure-free operation of the hydropneumodrive:

$$P_{min}(t) = P_{ME}(t) \cdot P_{Basis}(t) \cdot P_{IE}(t) = P^R(t) .$$

If the hydropneumodrive does not contain a memory element, then:

$$P_{min}(t) = P_{Basis}(t) \cdot P_{IE}(t) = P^R(t) .$$

Proceed in the same way if the hydropneumodrive doesn't contain intermediate elements or, if the hydropneumodrive doesn't contain both memory elements and intermediate elements.

2. Algorithms for calculating quantitative reliability indices for hydropneumodrives implemented by the standard positional structure method and the minimisation method. All reliability indices of the designed systems must ensure normal functioning of the systems during the specified service life. It is known that the main reliability indices are unambiguously related to each other by appropriate mathematical dependencies. Therefore, it is sufficient to define some of them. When analysing hydraulic-pneumatic drives as systems consisting of a certain number of elements, it is convenient to use such an indices as probability of failure-free operation, which refers to quantitative indices of reliability [6, 7].

For hydropneumodrives, which are implemented by the standard position structure method [9–11], the algorithm for calculating quantitative reliability indices at the design stage is as follows:

- decomposition – break down the complex system into elements and consider the quantitative and elemental composition of the command apparatus, based on the graph-operations and the principle scheme of the hydropneumodrive;

- using statistical and operational data of hydropneumatic drives similar to the designed ones, determine the average failure rate of the elements included in the drive;

- find the probability of failure-free operation of the command apparatus using the dependence:

$$P_{CA}(t) = P_{ME}(t) \cdot P_{\vee}(t) \cdot P_{\wedge}(t) .$$

In the cases considered in this paper, this dependence is generally represented as follows:

$$P_{CA}(t) = \exp\{-tn(\lambda_{ME} + \lambda_{\vee} + \lambda_{\wedge})\} ,$$

but may vary depending on the elemental and quantitative composition of the command apparatus;

- determine the other elements that make up the hydraulic pneumatic drive: select the basis and intermediate elements;

- calculate the reliability function – probability of failure-free operation of the basis $P_{Basis}(t)$ and intermediate elements $P_{IE}(t)$ (if there are intermediate elements in the hydropneumodrive, respectively), taking into account their elemental composition;

- find the total probability of failure-free operation of the hydropneumodrive, which is synthesised using the standard positional structure:

$$P_{SPS}(t) = P_{CA}(t) \cdot P_{Basis}(t) \cdot P_{IE}(t) .$$

For hydropneumodrives synthesised by the minimisation method [9–11], an algorithm for calculating quantitative reliability indices at the design stage is implemented:

- decomposition – break down the complex system into components and determine the elemental composition of the hydropneumodrive, based on the system of logical functions and the principle scheme of the drive synthesised according to them;

- select the basis and intermediate elements of the hydropneumodrive;

- calculate the probability of failure-free operation of the memory element if it is a part of the hydropneumodrive;

- find the probability of failure-free operation of the basis $P_{Basis}(t)$ and intermediate elements $P_{IE}(t)$ (if there are intermediate elements as part of the hydropneumodrive, respectively), taking into account their elemental composition;

- find the total probability of failure-free operation of the hydropneumodrive, which is synthesised by the minimisation method:

$$P_{min}(t) = P_{ME}(t) \cdot P_{Basis}(t) \cdot P_{IE}(t) ,$$

if there is a memory element in the system or:

$$P_{min}(t) = P_{Basis}(t) \cdot P_{IE}(t) ,$$

in the absence of an ME. Proceed in the same way if the hydropneumodrive does not contain intermediate elements or, if the hydropneumodrive does not contain both the ME and intermediate elements.

If the calculated fault-free operation indices are lower than the required ones, then the units and sections of the hydropneumodrive, which most of all affect the fault-free operation of the unit as a whole, are determined, and measures to improve their reliability are developed. Such measures include: replacement of elements for more reliable ones; easing the operating modes of elements, for example, moving the element from the zone of high temperatures; reservation of elements or separate sections of hydropneumodrives; changing the design or manufacturing technology of separate parts and units of aggregates having low reliability. If necessary, the structure of the construction of functional sections of hydropneumodrives is changed [12, 13].

Conclusions. The obtained algorithms for distribution of normalised reliability indices at the design stage for hydropneumodrives realised by the method of standard positional structure and the method of minimisation allow to normalise reliability indices already at the early stages of hydropneumodrives design, which makes it possible to obtain optimal solutions of reliability questions at the subsequent stages of development of the unit life cycle.

The selected methods of calculation and determination of design relations for finding quantitative characteristics of failure-free indices of designed hydropneumodrives, implemented by the method of standard positional structure and the method of minimisation, allow to design highly reliable hydropneumodrives of new metal cutting equipment.

Evaluation of reliability indicators of hydropneumodrives at the stage of preliminary design allows to make a rational choice of structural scheme and parameters, to select appropriate materials and elements of scheme realisations.

References

1. Герман В. Ф., Панченко В. О., Гусак О. Г., Папченко А. А. *Надійність та експлуатація гідромашин і гідроприводів*. Суми: Сумський державний університет, 2016. 175 с.
2. Фінкельштейн З. Л., Андренко П. М., Дмитрієнко О. В. *Експлуатація, обслуговування та надійність гідравлічних машин і гідроприводів: навч. посіб*. Харків: НТУ «ХПІ», 2014. 308 с.
3. Chen J., Liu R. Reliability Research on Hydraulic System of Civil Aircraft. *6th International Conference on Machinery, Materials, Environment, Biotechnology and Computer*. 2016. P. 84–88.
4. Tikhenko V. Reliability prediction of a mechatronic hydraulic drive at the early design stages. *UJMEMS*. 2023. Vol. 9, no. 1. P. 17–25.
5. Chen D., Yao C., Feng Z. (2013). Reliability Prediction Method of Hydraulic System by Fuzzy Theory. *6th IFAC Symposium on Mechatronic Systems. The international federation on Automatic Control (10–12 April 2013, Hangzhou, China)*. Hangzhou: Elsevier Ltd, 2013. P. 457–462. doi: 10.3182/20130410-3-CN-2034.90001
6. Канарчук В. Є., Полянський С. К., Дмитрієв М. М. *Надійність машин*. Київ: Либідь, 2003. 424 с.
7. Birolini A. *Reliability Engineering: Theory and Practice*. Deutschland: Springer-Verlag GmbH, 2017. 666 p.
8. Васілевський О. М., Поджаренко В. О. *Нормування показників надійності технічних засобів*. Вінниця: ВНТУ, 2010. 129 с.
9. Sokol Ye., Cherkashenko M. *Syntesis of control schemes of drives system*. Kharkiv: NTU "KhPI", 2018. 120 p.
10. Lynnyk A., Cherkashenko M., Fatieieva N., Fatyeyev O., Ponomarov V. Synthesis and analysis of control schemes of hydropneumatic drives. *Bulletin of the National Technical University "KhPI". Series: Hydraulic machines and hydraulic units.* Kharkiv: NTU "KhPI". 2021. No. 2. P. 11–17. doi: 10.20998/2411-3441.2021.2.02
11. Fatyeyev O., Fatieieva N., Sushko S., Pastushenko A., Ponomarov V. Comparative Analysis of Design Methods for Pneumatic Control Systems. *Advances in Design, Simulation and Manufacturing VI. DSMIE 2023. Lecture Notes in Mechanical Engineering*. Cham: Springer, 2023. P. 23–32. doi: org/10.1007/978-3-031-32774-2_3
12. Orosnjak M., Jocanovic M., Karanovic V. Quality Analysis of Hydraulic Systems in Function of Reliability Theory. *Proc. of the 27th DAAAM International Symposium*. Vienna: DAAAM International, 2016. P. 0569–0577. doi: 10.2507/27th.daaam.proceedings.084
13. Jocanovic M., Sevic D., Karanovic V., Beker I., Dudic S. Increased Efficiency of Hydraulic Systems Through Reliability Theory and Monitoring of System Operating Parameters. *Journal of Mechanical Engineering*. 2012. Vol. 58, no. 4. P. 281–288.

References (transliterated)

1. Herman V. F., Panchenko V. O., Husak O. H., Papchenko A. A. *Nadiynist' ta ekspluatatsiya hidromashyn i hidropryvodiv* [Reliability and exploitation of hydraulic machines and hydraulic drives]. Sumy, Sums'kyy derzhavnyy universytet Publ., 2016. 175 p.
2. Finkel'shteyn Z. L., Andrenko P. M., Dmytriyenko O. V. *Ekspluatatsiya, obsluhovuvannya ta nadiynist' hidravlichnykh mashyn i hidropryvodiv* [Operation, maintenance and reliability of hydraulic machines and hydraulic drives]. Kharkiv, NTU "KhPI" Publ., 2014. 308 p.
3. Chen J., Liu R. Reliability Research on Hydraulic System of Civil Aircraft. *6th International Conference on Machinery, Materials, Environment, Biotechnology and Computer.* 2016, pp. 84–88.
4. Tikhenko V. Reliability prediction of a mechatronic hydraulic drive at the early design stages. *UJMEMS*. 2023, vol. 9, no. 1, pp. 17–25.
5. Chen D., Yao C., Feng Z. (2013). Reliability Prediction Method of Hydraulic System by Fuzzy Theory. *6th IFAC Symposium on Mechatronic Systems. The international federation on Automatic Control (10–12 April 2013, Hangzhou, China)*. Hangzhou, Elsevier Ltd Publ., 2013, pp. 457–462. doi: 10.3182/20130410-3-CN-2034.90001
6. Kanarchuk V. Ye., Polyans'kyy S. K., Dmytriyev M. M. *Nadiynist' mashyn* [Reliability of machines]. Kyiv, Lybid' Publ., 2003. 424 p.
7. Birolini A. *Reliability Engineering: Theory and Practice*. Deutschland, Springer-Verlag GmbH Publ., 2017. 666 p.
8. Vasilevs'kyy O. M., Podzharenko V. O. *Normuvannya pokaznykiv nadiynosti tekhnichnykh zasobiv* [Standardisation of reliability indicators of technical means]. Vinnytsia, VNTU Publ., 2010. 129 p.
9. Sokol Ye., Cherkashenko M. *Syntesis of control schemes of drives system*. Kharkiv, NTU "KhPI" Publ., 2018. 120 p.
10. Lynnyk A., Cherkashenko M., Fatieieva N., Fatyeyev O., Ponomarov V. Synthesis and analysis of control schemes of hydropneumatic drives. *Bulletin of the National Technical University "KhPI". Series: Hydraulic machines and hydraulic units.* Kharkiv, NTU "KhPI" Publ., 2021, no. 2, pp. 11–17. doi: 10.20998/2411-3441.2021.2.02
11. Fatyeyev O., Fatieieva N., Sushko S., Pastushenko A., Ponomarov V. Comparative Analysis of Design Methods for Pneumatic Control Systems. *Advances in Design, Simulation and Manufacturing VI. DSMIE 2023. Lecture Notes in Mechanical Engineering*. Cham, Springer Publ., 2023, pp. 23–32. doi: org/10.1007/978-3-031-32774-2_3
12. Orosnjak M., Jocanovic M., Karanovic V. Quality Analysis of Hydraulic Systems in Function of Reliability Theory. *Proc. of the 27th DAAAM International Symposium*. Vienna, DAAAM International Publ., 2016, pp. 0569–0577. doi: 10.2507/27th.daaam.proceedings.084
13. Jocanovic M., Sevic D., Karanovic V., Beker I., Dudic S. Increased Efficiency of Hydraulic Systems Through Reliability Theory and Monitoring of System Operating Parameters. *Journal of Mechanical Engineering*. 2012, vol. 58, no. 4, pp. 281–288.

Received 11.09.2023

Відомості про авторів / About the Authors

Фатєєва Надія Миколаївна (***Fatieieva Nadiia***) – кандидат технічних наук, доцент, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0001-6955-5301; e-mail: nadin_yak@ukr.net

Фатєєв Олександр Миколайович (***Fatyeyev Oleksandr***) – кандидат технічних наук, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0002-9212-4507; e-mail: fatyan1@ukr.net

Поляков Валерій Валерійович (***Poliakov Valerii***) – Національний технічний університет «Харківський політехнічний інститут», магістр кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; e-mail: valerii.poliakov@mit.khpi.edu.ua