УДК 621.9 DOI 10.36910/775.24153966.2024.77.25

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СУЧАСНИЙ СТАН ВИНАХІДНИЦТВА, ВИРОБНИЦТВА, АНАЛІЗ РАНІШЕ ВИКОНАНИХ ДОСЛІДЖЕНЬ І ПЕРСПЕКТИВИ СТВОРЕННЯ МОТОР-ШПИНДЕЛІВ

Стаття присвячена аналізу сучасного стану винахідництва та виробництва мотор-шпинделів (М-Ш) для металообробних верстатів. Здійснено патентно-інформаційний аналіз, виявлено провідних виробників у Німеччині та Китаї. Зазначено різноманітність М-Ш та їх застосування у верстатобудуванні. Також розглянуто базу даних провідних розробників та виробників М-Ш для металообробних верстатів.

Ключові слова: *винахідництво, мотор-шпинделі, виробництво, патентно-інформаційні дослідження, верстати, металообробка.*

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THE CURRENT STATE OF INVENTION, PRODUCTION, ANALYSIS OF PREVIOUS RESEARCH AND PROSPECTS FOR CREATING MOTOR SPINDLES

The article investigates the contemporary state of invention and production of motor spindles (M-S) for metalworking machines. It conducts a patent-information analysis, identifying leading manufacturers in Germany and China. The diverse applications of M-S in machine tool construction are outlined. Additionally, it explores a database of prominent developers and manufacturers of M-S for metalworking machines.

Keywords: *invention, motor spindles, production, patent-information research, machine tools, metalworking.*

1. Results of patent information research

One of the main machine components that provides forming movements in the cutting process on turning, drilling, milling, aggregate, grinding and other machines with rotary movement of a part or tool has always been a spindle unit (SU) as a drive for the main movement. Over time, during the evolution of the spindle unit, the kinematic chain from the energy source to the output link (part or tool) was shortened and turned into a single unit that combines the energy source, energy converters, transmission and amplification circuits and the actuator - a spindle with a clamping device for a part or tool in one whole. These are electric spindles, which have recently been called motor spindles (MS). The M-S is seen as one of the main elements representing the machine tool and is becoming a key object on the way to the transition to smart manufacturing.

Patent information research made it possible to identify trends and directions of technical improvements, to develop models of macro- and micro-evolution of M-S structures, and to determine a control sample of objects (evolutionary events).

Patent searches for inventions (utility models) were conducted for different countries of the world on the Internet (http://gb.espacenet.com), for Russia (http://fips.ru), for Ukraine in the "Databases and Information and Reference Systems" (www.ui pv.bases2.htm1) in the section "Specialized Database "Inventions (Utility Models) in Ukraine".

Using various keywords, 2195 patents and copyright certificates for inventions and utility models were reviewed, of which 1250 patents were selected for further analysis after a thorough study of the translated content and illustrations in the titles of protection, i.e. the sample size was N_P = 1250). The chronological depth of the search is 64 years (T_E = 64).

The search for patent information was carried out under the IPC headings: H02K41/00; H02K1/06; H02K5/173; B23B17/00; B23B19/00; B23B19/02; B23B47/00; B23B47/06; B23Q1/70; B23Q3/00; B23Q5/00; B23Q5/10; B24B41/04; B24B47/12; F16C32/00.

The number of objects (control sample) is 104 objects (the power of the control sample of evolutionary events N_{PK} = 103). The geography of patent holders' countries within the control sample is presented in Table 1 and Fig. 1.

According to the search results, it can be stated that patents on M-S were found in 9 countries. But most of all in China, the USSR, Ukraine and Russia, which allowed us to limit further search for the countries of origin (probably developers and researchers, which can only be assessed by publications due to commercial secrecy).

It should be noted that China became interested in and began to engage in M-S much later than other countries, with a high intensity of development, acquisition of rights to them and their commercialization with the advantage of technology transfer to other countries of the Euro-Asian and American continents. This is evidenced by the revised catalogs of different countries.

Table 1.

Distribution of the number of patents by patent holder countries included in the control sample

UA		SU	RU	CN	US	DE	JP	FR	SK
20	N_{PK}	18	11	36	8	6	2	2	1

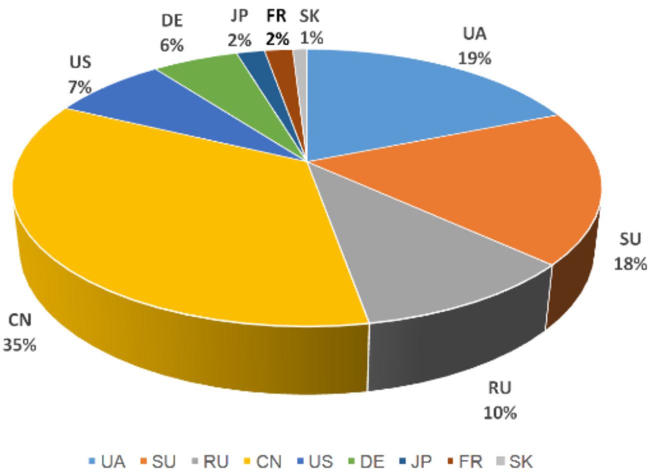


Figure 1. **Share of patent-holding countries within the control sample**

2. Motor-spindle manufacturers [3-6, 8-10]

Therefore, based on the results of the patent search, review of publications and a number of catalogs of M-S manufacturers, the main attention was focused on 2 countries: Germany and China.

It has been established that there are more than 300 manufacturing companies in Germany (+GF+, BIAX, HSD, ZIMMER, BENZ, FISHER, GMN, SIEMENS, HSTec, Setco, BIGKAIZER, SRUTER, BZT, ISEL, HITECO, WOLONG, KURODA, NAKANISNI, TDM, ...), which produce up to 400 types of M-S for various machine tools (milling, turning, grinding, multipurpose, woodworking and special-purpose), but there is not much information about the designers and researchers.

At the same time, Chinese government agencies, scientists and industrialists pay great attention to the design, research and production of M-S, with the involvement of specialists from other countries, including Europe and the United States.

According to the partially completed search for countries and companies producing M-S, they are currently produced in the following countries: Japan (JP), Germany (DE), France (FR), China (CN), Italy (IT), Russia (RU). The most famous manufacturers in these countries are: DMU, ELTE, Franz Kessler, Weiss, Diebold, Antecs, Cytec, Henninger, IMT, NSK, FANUC, KITAGAWA, HOWA, SUDA, SIEMENS, SAUTER, GRUNDFOS, DUPLOMATIC, SMW AUTOBLOC and others.

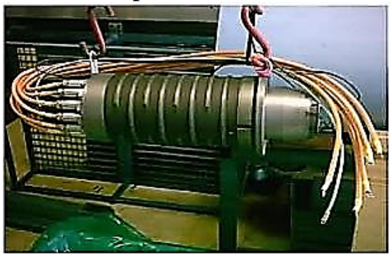
Below are examples of electromechanical systems (EM systems) of the M-S type, which are most widely used in production (Fig. 2-8). These EMSs are non-self-propelled, i.e., they provide only rotational motion n, and additional non-axial feed drives are used for translational motion of the spindle.

M-Ss belong to a special class of complex dynamic systems of natural and natural-anthropogenic origin that can realize both translational and rotational motion and represent a variety of evolving species. Such systems are used in metalworking complexes, turning, milling, drilling, grinding, multipurpose and other machine tools.

The idea to reduce the number of gearing mechanisms of the gearbox was embodied in the creation of M-S, which combined a drive motor and the spindle itself. The first M-S began to appear in the 70s of the twentieth century as motor-spindle assemblies for wrenching machines. With the further development of technology in the machine tool industry, motor-spindles began to appear that could realize the feed movement with the help of gears and couplings, using pneumatic systems, using hydraulic systems, using screw gears, etc.

The spindle unit manufactured by IBAG (Fig. 3, a) are adapted to all toolholders known on the world market. The integrated clamping systems HSK according to DIN 69893, BT, BBT, IBAGSKI, SKCAPTOCoromant are selected by customers depending on the size of the spindle and the maximum rotational speed required.

The IBAGSKI system is preferred for small and medium-sized spindles, while the HSK is recommended for spindles with a diameter exceeding 120 mm.




a) b)

c)

Fig. 2. **Motor spindles of the company: a - DMU and DekelMah, b - Artikelnummer, c - HFK with water cooling**

a) b) c)

Fig. 3. **Motor spindles: a - IBAG medium-sized for drilling, milling and high-speed machining;**
b - small-sized for engraving with high precision; c - powerful large-sized for manufacturing molds and dies in the automotive industry

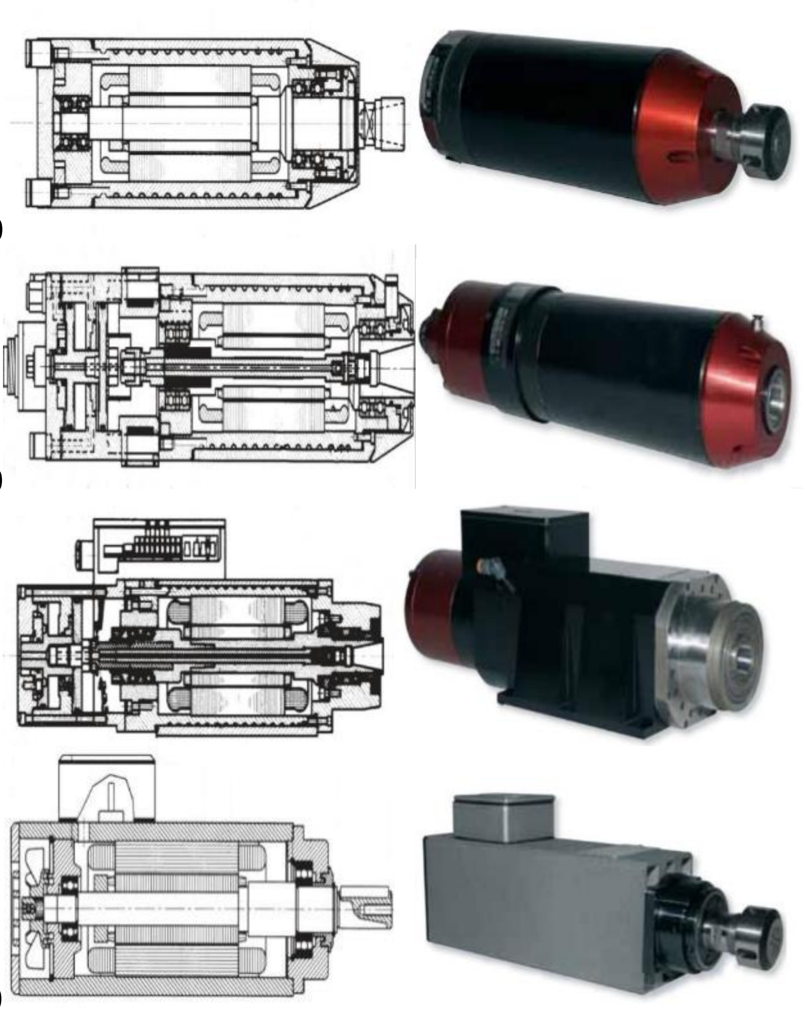
a) b)

Fig. 4. **Motor spindles with magnetic (a) and hydrostatic (b) bearings**

High-speed liquid-cooled M-S ELTE (Fig. 5, a) of the AF series are designed to be used as the main motion drive for milling and engraving machines and mold making machines.

The AF CU is the newest series of liquid-cooled M-S ELTEs (Fig. 5, b). It was developed on the basis of the AF series and is characterized by the presence of a quick-change chuck for clamping the tool.

ELTE PE series M-S (Fig. 5, c) are designed specifically for use in cutting machines and are designed for operation with increased axial and radial impact loads.



a)

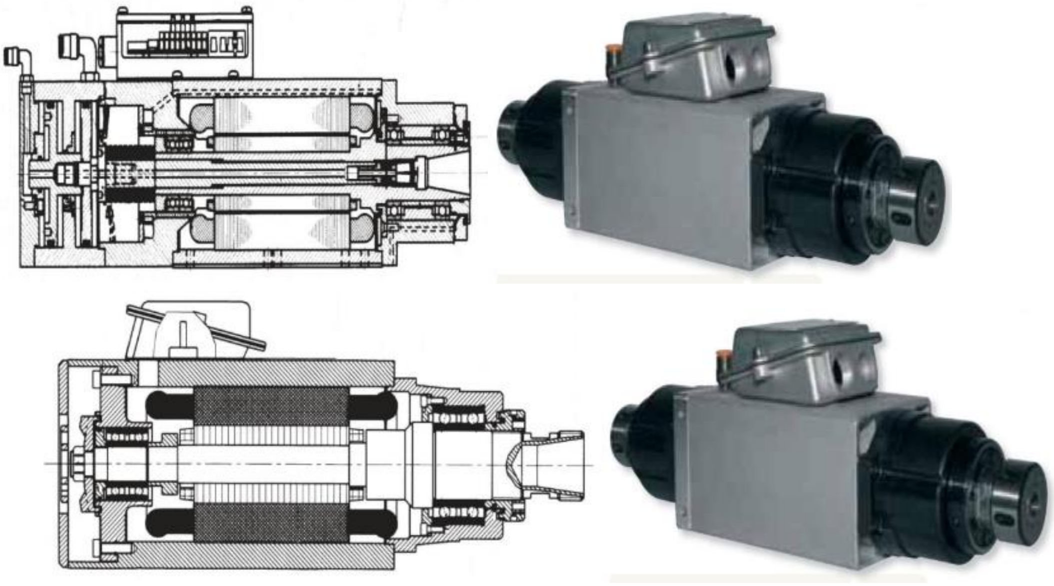
b)

c)

Fig. 5. **ELTE high-speed spindles of the AF (a), AF CU (b) and PE (c) series**

TMA is a series of high-speed M-S ELTE with automatic tool change (Fig. 6, a). The spindles are equipped with a forced ventilation system. Bearings and motor windings are cooled by compressed air and a built-in independent fan.

Thus, the results of the patent information search indicate that the class of EM systems of the "motor-spindle" type is a powerful class of EM transducers that is developing. Therefore, research and innovative developments in this area are currently relevant and promising.



a)

b)

Fig. 6. **Motor spindles of TMA (a) and TMPE (b) series by ELTE**

M-S ELTE of the TMPE series (Fig. 6, b) are equipped with a collet clamp and are designed to work with a tool loaded in both axial and radial directions.

According to the principle of operation, M-S are of alternating (synchronous and asynchronous types) and direct current. The most widely used are asynchronous and synchronous motors. The type of motor is primarily chosen depending on the required diameter and length of the gearbox, operating mode, power and number of revolutions. The type of cooling, the type and number of bearings, the tool clamping system, and the winding connection scheme are also taken into account. Built-in asynchronous motors are usually three-phase and are driven by special electric drives - HF (high frequency) frequency converters.

M-S are mass-produced with diameters ranging from 16 mm to 360 mm. The number of revolutions varies from 8000 rpm to 80000 rpm. The power for asynchronous M-S ranges from 1.2 to 100 kW, and for synchronous M-S from 4.2 to 82 kW.

In M-S, the size and power of the motors that drive the rotary motion are strictly limited by the dimensions of the spindle. Bearing dimensions are also a critical factor in spindle design.

The geometrical parameters of the motor rotor determine the selection of bearing sizes, which in turn determine the load capacity, stiffness and maximum spindle speed, so the motor characteristics must be matched to the bearing capabilities.

As well as spindle motors in various designs, Siemens offers complete motor spindles. The modular range of motor spindles covers milling, drilling, turning and grinding applications. Siemens' expertise in M-S is concentrated in the subsidiary Weiss Spindeltechnologie GmbH.

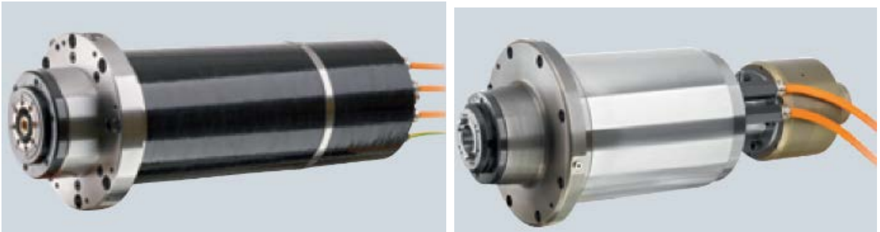
The company produces M-S for milling, turning and grinding. In addition, Weiss Spindeltechnologie GmbH also designs and manufactures customized solutions. They can be designed with an available power range of up to 130 kW and up to 1250 Nm without a gearbox or up to 3280 Nm with an integrated gearbox. M-S are available with synchronous and asynchronous motor technologies.

Figure 7 shows the variants of SIEMENS motor spindles.

The Chinese company Changzhou LINNAN Special Motor Factory was founded in 2013 and is a technological and professional manufacturer of spindles for air-cooled CNC machines, engraving spindles, water-cooled and air-cooled M-S spindles, spindles with automatic tool changers, etc.

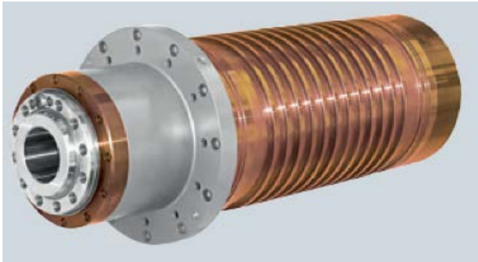
Fig. 8 shows the M-S mod. GDZ70X65-700W with air cooling, rated power 700 W, maximum rotation speed 18000 rpm.

Fig. 9 shows the milling M-S mod. GDZ85-2.2KW with a power of 2.2 kW and a maximum rotational speed of 24000 rpm. The milling machine is directly cooled by air, which makes it possible to operate safely and reliably in the event of dust and coolant splashes. This type of M-C is usually maintenance-free, as the AC motor does not have a commutator in its design.



a) milling motor spindles

b) compact milling spindle motor



c) compact lathe spindle motor

d) compact grinding spindle motor

Fig. 7. **SIEMENS motor spindles: a) SP series - mod. 2SP120 and mod. 2SP125); b) F series - mod. F150A); c) D series - mod. D175/375), d) S series - mod. SM120)**

Fig. 8. **Spindle motor mod. GDZ70X65-700W with air cooling**

Fig. 9. **Milling spindle motor mod. GDZ85-2.2KW**

Fig. 10 shows the M-S milling machine mod. GDZ120X103-6KW with a power of 6 kW with a clamping collet, a maximum rotational speed of 18000 rpm and a low noise level.

Fig. 10. Milling spindle motor GDZ120X103-6KW

3. Database of leading developers, researchers and manufacturers of motor spindles for metalworking machines [2]

The database was created based on the results of an information search and analysis of open access information resources (promotional products; catalogs; prospectuses of international specialized exhibitions; information digests, etc. The database contains organized information on leading European research institutions, companies and manufacturers of modern motor spindles (Germany, Switzerland, Italy, as well as developers and manufacturers in Japan, China and Taiwan) whose products are intended for CNC machines, metalworking centers and special-purpose machines. The database contains brief information on the name and country of the developer (manufacturer), the main areas of research and development and types of market products, contact addresses of their head offices and consulting centers, as well as up-to-date information on the presence of representative offices in Ukraine.

The leading firms and companies involved in the development, research and production of motor spindles include:1. FISCHER Spindle Group AG. 2. Siemens Electric motors, Spindel- und Lagerungstechnik Fraureuth GmbH, Neudecker & Jolitz (Himmel), BZT Maschinenbau GmbH, CNC-STEP GmbH & Co. KG, CTR Norte GmbH & Co.KG, Fiege, Weiss Gmb (Germany). 3. Teknomotor, HSD SpA (Italy). 4. BIG KAISER, TDM SA, GF Machining Solutions - Step-Tec, IBAG Switzerland AG, FISCHER AG - Präzisionsspindeln, TDM SA (Switzerland), MicroLab, Precision Technology Co., Ltd. Spintech Precision Machinery, Akira-Seiki Co., Ltd (Taiwan), Changlong Motor Co., Ltd. (China). FANUC (Japan).

4. Prospects for the development of motor spindles [1,11]

M-S systems are complex combined electromechanical structures that include mechanical and electromagnetic parts. The mechanical part includes the spindle itself, and the electromagnetic part includes the windings that are the source of the electromagnetic field.

The combined EM system is a spatial composition of at least two elementary structures, each of which performs its own function in the system (Fig. 11). Therefore, in such a combined system, the spatial shape and number of moving and stationary parts, air gaps, power and control systems is determined by a specific target function, the corresponding spatial geometry and the number of combined elementary EM structures.

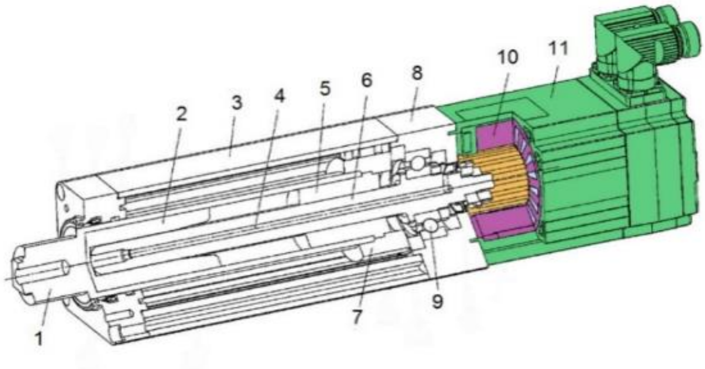


Fig. 11. **Motor-spindle in section: 1 - spindle; 2 - support cylinder; 3 - housing of the mechanical part M-S; 4 - lubrication compartment; 5 - spindle running gear; 6 - spindle nut; 7 - centering guide; 8 - casing; 9 - bearing; 10 - motor stator; 11 - motor housing**

The main attention was paid to the self-propelled M-S, in which the main motion and feed drives with a helical gear are combined (Fig. 12).

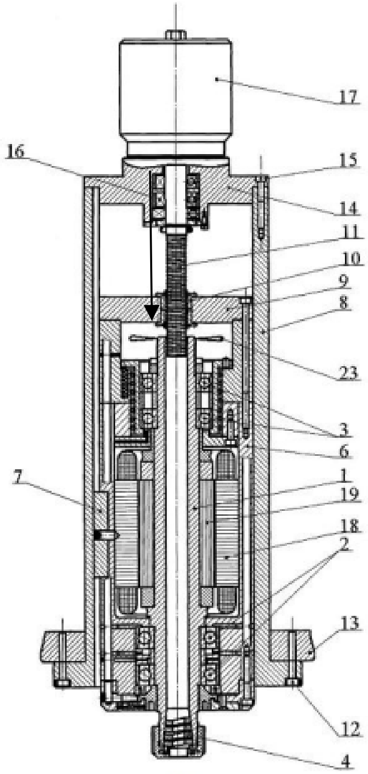
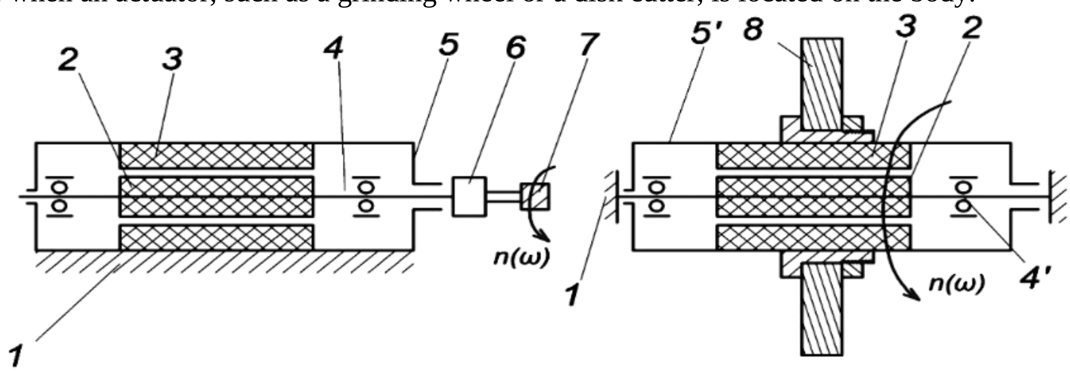


Fig. 12. **Self-acting M-S according to the patent of Ukraine No. 65488 on the basis of M-S by EBAG: 1 - spindle; 2 - front support; 3 - rear support; 4 - collet clamping chuck; 5 - cover with seals; 6 - M-S body with foam function; 7 - key; 8 - flange-type body; 9 - cover with nut10; 11 - feed screw; 12, 15 - fixing screw; 13 - movable platform of the MPS; 14 - cover; 15 - supports for screw 11; 17 - stepper motor for feeding**

The design of self-propelled M-S can be different, which affects the construction of calculation schemes taking into account the range of guides, their location, including on machines with parallel structure mechanisms (PSM). Stiffness, accuracy, and dynamic characteristics depend on the design. For example, when changing the scheme of electric current supply to the stator and rotor windings, M-S can be used both with a fixed body (Fig. 13, a) in the traditional design, when an actuator, such as a cylindrical cutter in a clamping chuck, is located on the rotor axis, and with a movable body with a fixed rotor (Fig. 13, b), when an actuator, such as a grinding wheel or a disk cutter, is located on the body.



a) b)

Fig. 13. **M-S with moving rotor (a) and stator (b) using the genetic inversion operator: 1 - fixed base; 2 - rotor; 3 - stator; 4 - rotating spindle; 4 - non-rotating spindle-shaft; 5 - fixed M-S body; 5' - moving M-S body; 6 - clamping chuck; 7 - cylindrical cutter; 8 - grinding wheel.**

One of the schemes of a self-acting M-S with a helical gear is shown in Fig. 14.

When voltage is applied to the stator winding 4, a magnetic field is generated that interacts with the two-layer active surface of the rotor 6 and thus causes the spindle 7 to rotate at the required speed n. To ensure the feed of the spindle, voltage is applied to the electric motor 1, the revolutions of which are converted by the CNC system through the screw pair 2, 3 into the translational movement of the pinola 5, providing the required feed S. Options for the technical implementation of the synthesized chromosome S_{33} will be discussed in Section 2.4.

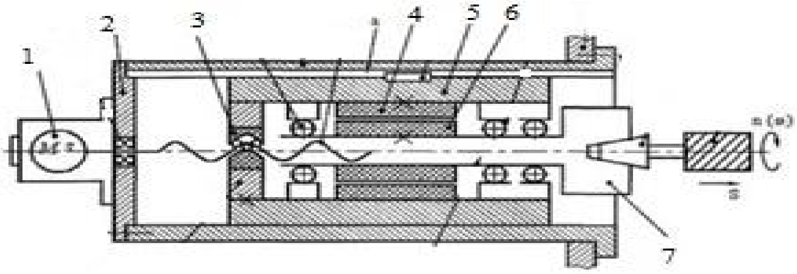
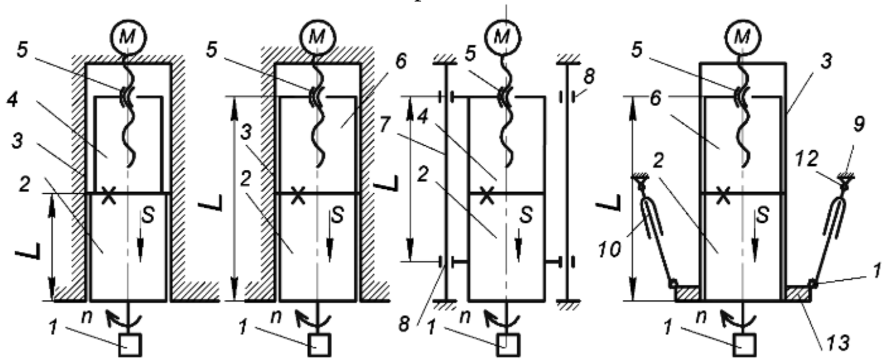


Fig. 14. **Principal kinematic diagram of a self-acting M-S flange type**

The following 4 design schemes were selected for use in different machines (Fig. 15):
a) with a base for guides along the length of the M-S body;
b) with an increased base in length due to additional extension of the guides;
c) with guides in the form of fixed rods arranged in parallel in the plane of the M-S axis;
d) option "b" with its location on the movable platform of the machine with PSM.



а) б) в) г)

Fig. 15. **Constructive diagrams of variants of self-propelled M-S with a helical gear for further theoretical studies**

In embodiment 1 (Fig. 15, a), the body M-S 2 of the traditional design is rigidly connected to the cup 4, in which the nut of the screw pair 5 (sliding or rolling) is located, the screw of which receives revolutions from the stepping or tracking electric motor M according to the program from the machine's CNC system. This, in addition to the revolutions n of the main motion tool, provides coordinate movement with the feed S of the M-S 2, as pinions in the guides 3.

To increase the stiffness of the spindle assembly in variant 2 (Fig. 15, b) by reducing the skew angles, the pinion is extended by a glass 6, which is made of the same diameter as the body M-S 2.

It is possible to perform the guides in the form of fixed parallel rods 7 (Fig. 15, c) with sliders 8 at a distance L. In this case, it is not necessary to perform the glass 6 according to the scheme in Fig. 6, b, but it is possible to use the glass 4 according to the scheme in Fig. 6, a.

Option 4 provides for the location of the spindle assembly on a movable platform 13 (Fig. 15, d) of a machine with a parallel structure mechanism (PSM) and rods 10, which are connected to the platform by means of hinge joints 11, and hinges 12 to the fixed part of the machine. It is possible to make rods of variable length or constant length, where the upper joints of the connection are located on gradually moving slider supports, the movement of which is set by the CNC system. The location of the self-propelled M-S on a movable platform allows machining surfaces or holes at an angle using the feed S of the self-propelled M-S, rather than the movements of the entire platform with a larger mass (Fig. 16).

Conclusions and recommendations

1. The results of the patent information research made it possible to carry out a thematic patent search for inventions (utility models) related to M-S for machine tools for various purposes, to find competitors and possible partners in the creation of new designs and to determine the role of Ukrainian scientists in this area with high probability.
2. It has become obvious, as a global trend in high-speed machining, the transition from multi-link drives of the main rotational motion to a single-link drive, where the spindle assembly of the machine

is made in the form of a M-S, the stator of which is the body of the spindle assembly (spindle headstock), and the rotor is a spindle with an end for fixing a tool or part.

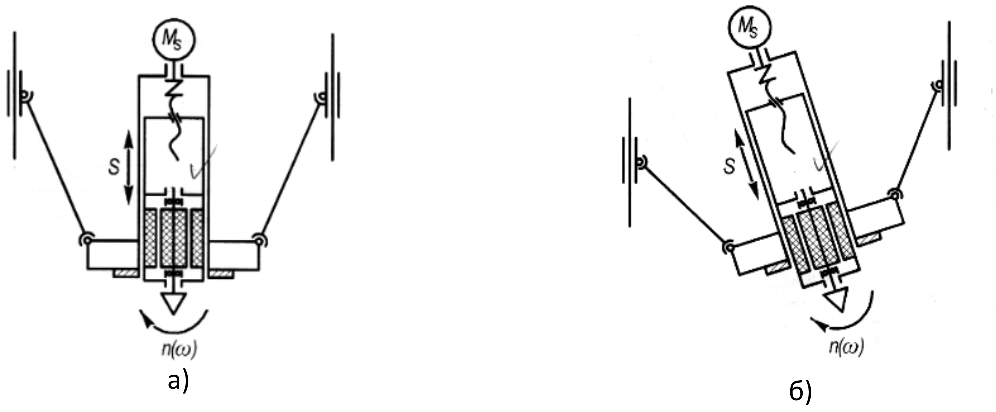


Fig. 16. **An example of using a self-powered M-S on a machine with an PSM and rods of constant length: a - vertical position; b - angular position**

3. Currently, M-S are manufactured for various machine tools (milling, turning, grinding, multi-purpose, woodworking and special-purpose), but the vast majority are for milling machines with supports in the form of liquid-cooled ball bearings and collet clamps.

4. Self-acting M-Ss that perform rotational (main drive function) and translational (feed drive function) forming movements are still not manufactured. It was possible to combine these movements in the design of the M-S due to the universal genetic crossing operator, which made it possible to move to hybrid systems that became the object of this research.

5. The pioneers in the creation of self-powered (hybrid) M-S were scientists of the departments of machine design of the Institute of Mechanical Engineering and Electromechanics of the FEA of Igor Sikorsky Kyiv Polytechnic Institute, as an example of an interdisciplinary approach to solving current problems.The next step in the improvement and monitoring to improve the technical and economic performance of CNC machines and expand their functionality in remote control is the creation of intelligent M-S.

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