Mechatronics and selected issues of the linear servo motors

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The paper presents state–of–the–art in the mechatronics area, describes the comprehensive problems and trends of future development. Some selected issues concerning mechatronic servodrives are discussed, among which attention is paid to gearless drives with linear motors both asynchronous and synchronous and with high-energy permanent magnets. Then the results of steady-state and transient analysis are reported, and positive and negative features of both type of motors are displayed.

In the summary the conclusions are formulated and the Authors have stated that currently the mechatronics area covers various spheres of industry and socio-existential human life.

Keywords and phrases: mechatronics, electric drive, transient processes, linear induction motor, synchronous linear motor.

The beginnings of the development of mechatronics

The first scientific papers concerning mechatronics were published in Japan in the 1970s during the development of mechanisms with high level of precision and computer control. It was the first time when the term "mechatronics" was used — to call an electronic controller for an electric motor — by the Japanese engineer of the Yaskawa Electric Corporation, legally protected until 1982. In 1983 the commencement of issuing the magazine "Mechatronics" was noted and next in 1984 seven books concerning the mechatronics were published as well. In 1985 the Mechatronics Centre at the University of California was created with research program in which twenty companies participated. In Poland, the term "mechatronics" was disseminated in 1980s by Prof. Władysław Tryliński from the Warsaw University of Technology. In 1996 the Faculty of Fine Mechanics of this University was transformed into the Faculty of Mechatronics. Scientific and research institutions played a major role and among others there should be noted the Industrial Institute for Automation and Measurements, Institute of Fine Mechanics in Warsaw and Research and Construction Centre in Pruszków [1, 2].

As K. Kluszczyński aptly pointed out "mechatronics developed from electrical engineering by electronics and robotics to mechatronics" [3], and "without electric energy and electrical engineering there would not be mechatronics". Just the development of electricity and magnetism in the nineteenth and twentieth century ensured a spread of electric energy and the creation of a series inventions, devices and electrical apparatus. For these reasons, the twentieth century was called the age of electricity.

It should be noted that the first automatic machines have already appeared in the ancient times. In 400 BC, Archytas of Tarent invented mechanical toys, including wooden pigeon, which, according to historical sources, could fly. Moreover, it is considered that the most complicated automaton was made in 1774 by Dros Jaquet, showing a girl playing the clavichord. Recall that the term "robot" was used for the first time by the Czech writer Karl Čapek in 1920 in his fantastic and scientific drama. Among many other inventions of the first half of the twentieth century, Piraux's "electronic dog" (1929) and Grey's "cybernetic turtle" (1949) [2] should be mentioned.

Today, mechatronics is a new branch of science being a combination of mechanical, electrical and computer engineering and automation and robotics as well.

Currently this branch is growing rapidly, and its needs have been specified by the contemporary market and an answer came just from the industry of advanced technologies, proposing a new quality products, called “mechatronic products”.

In the literature we can find different definitions of mechatronics depending on professional speciality and the needs of their creators. Among them let us note an approach to the subject, which is close to the point of view of the Authors and is presented in this publication — a proposal of Prof. J. Turowski — “Mechatronics means philosophy and technique of synergistic design of machines and processes capable for an intelligent behaviour with an inseparable combination of mechanics, electronics, computing, and the dynamic electrodynamics and system thinking and economics” [4].

Current areas of application

We can repeat after B.Z. Sandler that any technical device, in our case a mechatronic device, can be presented as a connection between three basic elements: tool, energy and control. In the early stages of the development of mechatronics the water energy, gravity forces, muscle energy were used, and next spring, pneumatic and hydraulic drives were applied also. Increased requirements have caused the application of electric drives. Now it has been estimated that they constitute more than 50% of the drives.

Today, in the manufacturing process of new mechatronic products, particular attention has been paid to the competitiveness of the product and acceleration of the production cycle. In order to enhance innovation, there are carried out intensive research works on application of improved actors, and among them electric motors of a new generation are playing an important role. In this context a modern unconventional electric motor retains its extremely important key position in a mechatronic drive.

The devices for sound recording and sound reproduction are good examples illustrating the evolutionary transition from mechanical to mechatronic solutions. These products should be characterized by a high market demand. Current areas of mechatronics’ application are very wide and cover practically all spheres of life. At this point let us mention the most well known spheres of present application of mechatronics [1–10]:

— Rail transport, automotive engineering and other unconventional means of transport, e.g. wheelchairs.
— Advanced consumer appliances, applied to meat products, food products and consumer electronics.
— Medical devices for diagnostics and operations.
— Computer and office equipment.
— Photo and video technology.
— Numerically controlled machine tools and industrial robots.
— Metrology, measurement tools, especially in nanotechnology.
— Aerospace technology.
— Technology for army, police and security services.
— Ocean technology including equipment for underwater apparatus.
— Intelligent Building Systems.
— Equipment for record-seeking sports.
— Means of communications and telecommunications.
— Simulators to train pilots.
— Printing machines.
— Smart devices for the entertainment industry.
— Modern toys.

This list can be further extended. Presently the market of mechatronic modules and systems is dynamically growing. New applications and requirements of mechatronic devices could be noted best in medical or military technology.

Modern mechatronic drives

The twenty first century can be called an age of mechatronics and information technology, as also is the nineteenth century — the steam age, and the twentieth century — the electricity age. As a result of technical progress in electrical engineering, micro-electrical engineering, computer technology and electro-mechanics of a new generation, a new branch called mechatronics there has emerged. Its development and modern solutions is closely linked with the progress of miniaturization and the working out of a new generation of linear motors with reduced electromagnetic and electromechanical time-constants. Direct linear drives in mechatronics are the future solution. It should be expected that they will be increasingly used. The principle of operation of such drives does not differ from the analogous solutions concerning classic motors.

A classic mechatronic drive usually consists of an electric motor, a high ratio reducer, electronic systems, electronic power modules and software. A typical mechatronic drive consists of an actor — electric motor, a gear with a high ratio (>> 10:1) or crank-gear, sensors, setting devices and power electronic supply systems. The software has been included as well.

The requirements for speed, accuracy, decreasing the time of transition can be ensured by a mechatronic drive with linear motors, allowing one to simplify the kinematic diagram of the mechanism and to eliminate the gear. The gear brings into a drive not only its own weight and volume, but clearances as well; it modifies also elastic nature of the connection, the moment of inertia and other parameters.

However, drives with linear asynchronous and synchronous motors with permanent magnets [11, 12] allow one to eliminate the gear. In addition to the important advantages of linear motors we can include: large values of acceleration and speed, the ability to work in various weather conditions and over a wide temperature range, perfectly quiet work, no sparks, the simplicity of connecting several motors in one unit with increased power output, respectively, the so-called modular connections. All of these benefits are paid for by a significant reduction of energy indicators of these machines in relation to rotary machines. In these machines peculiar phenomena are noted, and particularly the longitudinal end effect. When designing such a drive it is important to analyze electromagnetic, electromechanical and thermal transitions. [13, 14].

Electric linear drives are the design solutions of a new generation, they have been used in drive systems of machine tools, and allow one to ensure an increase in:
— positioning accuracy by an order higher (up to about 0.1 micrometer);
— speed of feed motion (from 30/60 to about 700 m/min);
— acceleration of motion in transient states (from 10 to 120 m/s^2);
— complex travelling path of machine tools (from 6 to 50 m);
— control dynamics.

These motors have a greater acceleration (however they require cooling of both primary and secondary part). The largest accelerations and overload are developed by the synchronous motor with permanent magnets.

Selected aspects of linear servodrives

The most important requirements for modern mechatronic modules are precision and very high accuracy of movement. According to the publication [7] the modern technological equipment should meet the following requirements:
— acceptable error of form 0.01–0.1 micrometer,
— smoothness of the worked surface R_a — 0.002–0.01 micrometer,
— movement step up to 5 nanometers,
— a small intersection of the chip (about 20 micro-meters²),
— exclusion of thermal deformations and vibration nodes.

Linear servo designer has to answer two fundamental questions: first one — Does the SIL meet requirements concerning permissible temperature for the type of work and class of insulation? And second question — What are the reserves to increase its load? For calculations specialized computer programs are used, e.g. MATLAB, Flux3D, COMSOL or Elcut.

Analysis of the literature regarding linear induction motors (SIL) allows one to come to a conclusion that researchers pay insufficient attention to the choice of mathematical models for analysis of processes in steady and transitional states — both electromechanical and thermal ones. It has been noted that still imperfect methods of calculation force the researchers and designers to verify theoretical calculations on test stands. The simplest, it seems, are test stands with the disk and secondary element; these stands allow one to examine the SIL regimes in engine, generating, brake and reversible modes.

The literature presents different models of SIL due to, among others, various degrees of adopted simplifications and computational procedures used in connection with the accepted mathematical models. Figure 1 shows the results of calculations of the electromagnetic force of F_e SIL type SL-5-270, produced in Poland, received on the basis of 11 selected methodologies [15]. You can see how large are the differences in the calculation of the electromagnetic force, which results from the just accepted simplifications and computational methods.

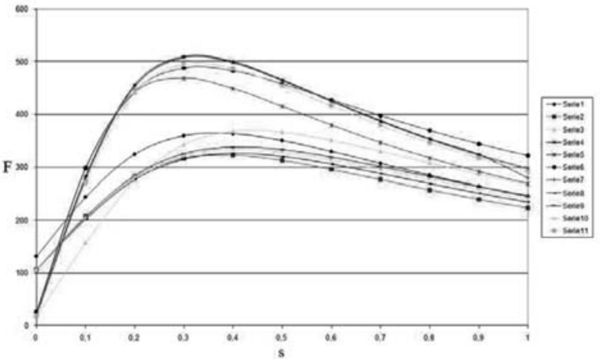

Fig. 1. Force characteristics SIL F_e = f (s) calculated on base of different methodologies [15].

Results of servodrive with the SIL in various states of work, especially at start-up and reverse is shown in Fig. 2 with a load of F_{obc} = 45 N. There is a noticeable impact of speed on the scale of the so-called longitudinal end effect of SIL (asymmetries and pulses with a double frequency have been created) At low speeds the amplitude of pulsation is close to zero, and with increasing speed their amplitude increases.

An important issue are the models to test the thermal processes SIL. As a rule, servomotor operates in non-stationary states, so there are necessary such methods of

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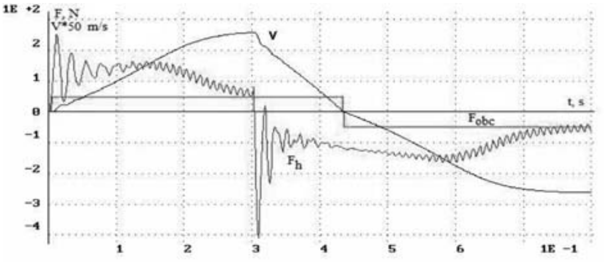

Fig. 2. Characteristics of F and v for the start-up and reverse of SIL.

calculations which allow one to obtain information with the required accuracy in the transient states about the heating of various elements of SIL. One of the proposals regards a method of detailed and supplementary heat diagrams (DZSC), which allows one — with consideration of the speed CzW SIL and the desired accuracy of the calculations — to examine electromagnetic, electromechanical and thermal processes [14]. Figure 3 shows an example of temperature of the secondary sections of the SIL in the case of its moving at a speed of 0.01 m/s. It follows from the cited charts that temperature of CzW areas outside the inductor in the direction of movement increases almost up to 60°C, and at this time its areas under inductor are heated-up weakly, because not heated "outlets" from the left side are approaching in turn permanently.

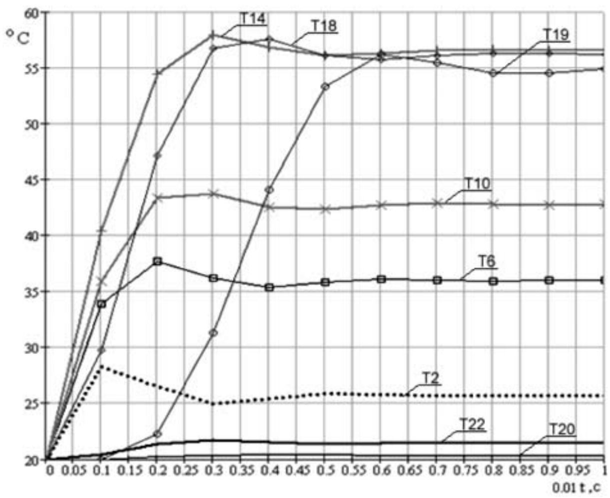

Fig. 3. Heating-up curves of the different construction elements CzW SIL of SL-5-270 type moving at a speed v = 0.01 m/s.

Within the framework of the thermal analysis of the induction linear tubular motor, carried out in an Elcut environment, the temperature distribution (Fig. 4) was obtained. The heat from the inductor of linear and tubular induction motor (LSTI) is put into the environment through convection and radiation [16]. Analyzing the temperature distribution (Fig. 4) it can be

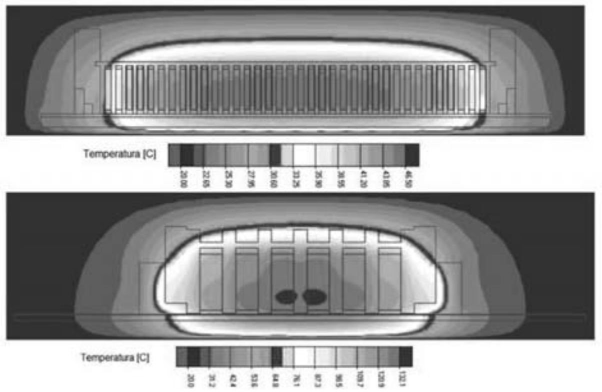

Fig. 4. Temperature fields of engines LSTI type: a) LC1, b) TW1.

noted that the maximum temperature LSTI is in halfway up the windings.

In recent years an increased interest of producers of mechatronics modules in using linear servomotors with three-phase synchronous motors with high energy permanent magnets has been noted [2, 5, 7, 12, 17, 18]. For example, in machine tools of new construction with a linear drive there is associated the term of a direct drive, i.e. that in which the motors are integrated with a guide mechanisms.

In practice, there are two construction solutions: with a moving system of permanent magnets and the stationary stator (with windings), and the movable stator and immovable system of magnets. The comparison of two constructional variants of such motor with progressive and turning movement has been presented in [18], which shows that the motors with a movable system of permanent magnets from rare earth have a definite advantage, mainly in the aspect of developing force feed. However, in servo drives of machine tools being under numerical control a stationary system of permanent magnets is usually employed, and the stator with windings is a movable element. Linear synchronous motors are characterized by more favourable parameters, e.g. the ratio of electromagnetic driving force to the motor weight is by 50–100% greater than the asynchronous linear motors and have a milder temperature regime than the analogous asynchronous motors.

Summary

In the early stages of the development of mechatronics, there was used the water energy, the gravity force, muscle energy, and next spring, pneumatic and hydraulic drives were implemented as well. The development of electricity science and increased requirements of the market forced the application of electrical drives to mechatronic systems, particularly with linear motors asynchronous and synchronous with permanent magnets. Such systems have several advantages: no gears, they allow one to develop higher value of the acceleration and speed and give the opportunity to work in various weather conditions.

The application of linear motors in drives' systems of mechatronic products is an interesting research and implementation perspective. But in order to work out a proper design of a drive in a mechatronic module with the linear motor as an actor and to use its advantages, it is necessary to choose adequate mathematical models, and next to carry out a comprehensive study in steady and transient states, and to estimate singular phenomena for this type of devices and its heat condition.

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