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Зав. кафедрой Шелудько В.Н.

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МАГИСТРА

Тема: «АВТОМАТИЗАЦИЯ КАЛИБРОВКИ ИЗМЕРИТЕЛЯ КОЭФФИЦИЕНТА СЦЕПЛЕНИЯ»
(«AUTOMATION OF CALIBRATION OF FRICTION COEFFICIENT MEASURER»)

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Санкт-Петербург
2018
GRADUATION THESIS TASK

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«___»_february _2018

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Thesis subject: Automation of calibration of measurer of coefficient of friction
Graduation work location: ACS department, Educational and Scientific Laboratory "Mechatronic complexes of mobile objects and mobile installations of special equipment", educational and Scientific Center "Siemens automation and electric drives"
Technical requirements:
Measuring horizontal force range (-30÷1000)N
Measuring vertical force range (300÷1000)N
Step motor step angle 1,8º

Thesis contents:
Classification of test benches, development of mechanical design of calibration platform, development of electric drive and data collection system

Deliverables list: Explanatory notes, graphic materials

Additional part: Special Security Issues

Task issue date  Thesis defence date
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<td>Electric drives and mechanical structure</td>
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<td>3</td>
<td>Data system</td>
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<td>4</td>
<td>Special Security Issues</td>
<td>28.04.2018</td>
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(Academic Degreee)  ___________________________  (Signature)
ABSTRACT

Explanatory note 84 pages, 39 figures, 8 tables, 31 sources.

FRICITION COEFFICIENT MEASURER, CALIBRATION, RESEARCH, TEST, DEVELOPMENT, PULLING FORCE, STEPPER MOTOR.

The graduation thesis purpose – development, creation of the stand for calibration of friction coefficient meter, creation of a methodical complex of tests.

Results of the work:

System testing method, functional diagram, algorithms and software of information control system implemented on a personal computer, wherein an independent ergonomic layout and application to the unique stand.
The topic of the work is “Automation of calibration of friction coefficient measurer”. A result of this work is a calibration platform (next STAND) for electromechanical friction coefficient measurer (next EMFCM).

In the first chapter there is a literature review in the field of test benches, dynamometer benches and its structures.

The second chapter shows design of the calibration platform: mechanical, electrical and software parts.

Methodology of the tests is described in the third chapter with some explanations.

Safety aspects are described in the fourth chapter.
CONTENTS

ABSTRACT ....................................................................................................................................................... 5

LIST OF ABBREVIATIONS .............................................................................................................................. 9

INTRODUCTION .................................................................................................................................................. 11

1. EQUIPMENT TESTS. TEST CLASSIFICATION ......................................................................................... 12
  1.1. Test classification ................................................................................................................................. 12
  1.2. Testing workbench ............................................................................................................................... 17
  1.3. Testing workbench classification ......................................................................................................... 18
       1.3.1. Groups of test benches for obtaining the dynamometric characteristics ........................................ 20
       1.3.2. Division of dynamometric test benches by the type of test object ..... 21
       1.3.3. Division of dynamometer test benches into subclasses according to the type of load device .......... 26
  1.4. Dynamometric structures. Dynamometric design of the stands for obtaining the power characteristics of
      the vehicles ............................................................................................................................................... 30
       1.4.1. Balance suspended stator ............................................................................................................ 30
       1.4.2. Torque sensor .............................................................................................................................. 34
       1.4.3. Direct measuring of force .......................................................................................................... 36
       1.4.4. Inertial dynamometric structure ................................................................................................. 38
       1.4.5. Indirect determination of the torque by measuring the tension of the chain or belt .................... 38
       1.4.6. Determination of the torque by the current ................................................................................ 39

2. THE DESIGN OF THE CALIBRATION PLATFORM ..................................................................................... 40
  2.1. Bench mechanical design development ............................................................................................... 40
       2.1.1. Principle of operation .................................................................................................................. 40
       2.1.2. Version 1. Mechanical layout .................................................................................................... 40
       2.1.3. Version 2. Mechanical design .................................................................................................. 43
  2.2. Stand components selection .................................................................................................................. 45
       2.2.1. Stepper motor selection .............................................................................................................. 46
       2.2.2. Stepper motor driver selection .................................................................................................. 47
2.2.3. Driver supply unit ................................................................. 48
2.2.4. Weighing terminal selection .................................................. 50
2.2.5. Sensors selection ................................................................. 52
2.2.6. Microcontroller selection ...................................................... 55
2.3. Control system design .............................................................. 56
2.3.1. Application of state transition graphs in control system .......... 56
2.3.2. Software functional requirements .......................................... 61
3. THE METHODOLOGY OF THE TESTS ...................................... 62
3.1. Preparation for the EMFCM calibration .................................... 62
3.2. EMFCM calibration ................................................................. 65
3.3. Measurement of the current radius of the EMFCM measuring wheel .... 68
3.4. Determination of the friction coefficient measurement error .......... 69
3.5. The results of the calibration ................................................... 69
3.6. Completion of EMFCM calibration ............................................ 70
4. SPECIAL ASPECTS OF SAFETY ................................................ 71
4.1. Electric safety ........................................................................ 71
4.2. A set of measures to ensure the electrical safety of the product .... 72
4.3. Neutral earthing ................................................................. 73
4.4. The calculation of the neutral earthing ..................................... 74
4.5. Electromagnetic compatibility ............................................... 76
4.6. The determination of the safety integrity level ......................... 78
4.7. Immunity test program ......................................................... 79
CONCLUSION ............................................................................. 81
REFERENCES ........................................................................... 82
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS</td>
<td>automatic control system</td>
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<tr>
<td>ADC</td>
<td>analog-to-digital converter</td>
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<td>AVR</td>
<td>family of microcontrollers developed by Atmel</td>
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<td>COM</td>
<td>serial port interface</td>
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<td>CDP</td>
<td>control and display panel</td>
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<td>DTC</td>
<td>direct torque control</td>
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<td>ECB</td>
<td>emergency circuit breaker</td>
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<td>ED</td>
<td>electric drive</td>
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<td>EGR</td>
<td>exhaust gas recirculation</td>
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<td>EMD</td>
<td>electromagnetic drive</td>
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<td>EMFCM</td>
<td>electromechanical friction coefficient measurer</td>
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<td>EP</td>
<td>earth plate</td>
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<td>ETU</td>
<td>Electrotechnical University</td>
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<td>FC</td>
<td>friction coefficient</td>
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<td>LC</td>
<td>load cell</td>
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<td>MLM</td>
<td>maximum limit of measurement</td>
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<td>MW</td>
<td>measuring wheel</td>
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<td>OTC</td>
<td>operating transmission coefficient</td>
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<td>PC</td>
<td>personal computer</td>
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<td>RAM</td>
<td>random access memory</td>
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<td>RMSD</td>
<td>root-mean-square deviation</td>
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<td>RTU</td>
<td>remote terminal unit</td>
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<td>SIL</td>
<td>safety integrity level</td>
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<td>STAND</td>
<td>metrological calibration stand</td>
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<td>STEP/DIR</td>
<td>step/direction protocol</td>
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<td>SW</td>
<td>support wheel</td>
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<tr>
<td>Abbreviation</td>
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<tr>
<td>TCP/IP</td>
<td>transmission control protocol and internet protocol</td>
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<td>TW</td>
<td>transport wheel</td>
</tr>
<tr>
<td>UART</td>
<td>universal asynchronous receiver-transmitter</td>
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<tr>
<td>UML</td>
<td>unified modeling language</td>
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<td>USB</td>
<td>universal serial bus</td>
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INTRODUCTION

Pre-flight friction properties measurement between covering surface and aircraft wheels is currently carried out at airports around the world by rolling with constant sliding of measuring wheels with the help of mobile (towed or self-propelled) installations.

Calibration of measuring instruments – a set of operations performed to determine the actual values of metrological characteristics of measuring instruments.

Calibration of measuring instruments is carried out mainly by metrological services of legal entities with the use of standards, accompanied by the state standards of units.

The procedure for calibrating the friction coefficient meter is carried out using the calibration platform for the developed calibration procedure.

The implementation of the automated electric drive (ED) in the calibration procedure of the friction coefficient measurer will simplify the process, will increase the accuracy of obtained results and will reduce the time of calibration, thereby reducing the friction coefficient measurer idle time.

Based on the initial data specified in the task for master’s thesis, it is necessary to develop the design of an automated stand, to conduct a reasonable choice of modern automation tools, which usage in the design will ensure the performance of the stand at a fixed limit of operating forces.
1. EQUIPMENT TESTS. TEST CLASSIFICATION.

Test – experimental determination of quantitative and (or) qualitative properties of the subject of tests as a result of actions on it, at its functioning, at modelling of the subject and (or) actions [1].

The test is performed with the purpose of obtaining necessary decision-making information on the conformity of the testing object to the specified requirements.

1.1. Test classification

To solve these problems, there are many types of tests that can be classified according to the following features:

1) by assignment:
   a. research,
   b. determinative,
   c. competitive,
   d. validation;

2) by conducting level:
   a. state,
   b. intra-departmental and departmental,
   c. factory;

3) by design and acquisition level:
   a. development,
   b. initial,
   c. commissioning,
   d. qualification;
4) by test assignment of the finished product:
   a. predelivery,
   b. acceptance,
   c. periodic,
   d. inspection,
   e. typical,
   f. release,
   g. certification;

5) by conditions and location:
   a. laboratory,
   b. bench,
   c. field,
   d. full-scale,
   e. model testing,
   f. actual;

6) by the duration:
   a. longitudinal,
   b. normal,
   c. accelerated,
   d. short-time;

7) by the type of effect:
   a. mechanical,
   b. climatic,
   c. thermal,
   d. radiation test,
   e. electric test,
   f. electromagnetic test,
   g. magnetic,
   h. chemical,
8) by the effect results:
   a. nondestructive,
   b. destructive,
   c. life,
   d. robustness,
   e. ruggedness;

9) by the defined characteristics of the tested object:
   a. reliability,
   b. safety,
   c. transportability,
   d. marginal,
   e. technological.

**Research tests** – tests conducted to examine (study) the characteristics of the properties of the test object.

**The purpose of research trials:**
1. The definition or evaluation of quality profiles of object;
2. Selection of optimal characteristics of the object and modes of its operation;
3. A comparison of the many variants of realization of the object in the design;
4. Selection of significant factors affecting the quality profiles of the object

**Definitive** – Test conducted to determine the values of the characteristics of the object with the given values of indicators of accuracy and reliability.

**Comparative** – tests of similar characteristics or same objects, carried out in identical conditions for comparison characteristics of their properties.

**Control** – Tests carried out to check the quality of the object.

**State** – tests of the established most important types of production which are carried out by head organization on the state tests, or acceptance tests which are
carried out by the state Commission or the testing organization to which the right of their carrying out is granted.

**Inter-departmental** – testing of products conducted by the Committee consisting of representatives of several concerned ministries and (or) departments.

**Departmental** – tests carried out by the Commission from representatives of the interested Ministry, Department.

**Factory tests** carried out by specialists of the enterprise.

**Finishing tests** – the research tests which are carried out at development of production for the purpose of the assessment of influence of the changes made in it for achievement of the set values of indicators of quality.

**Preliminary Control tests** of prototypes and (or) pilot batches of production for the purpose of determination of possibility of their presentation on acceptance tests.

**Acceptance Control tests** of prototypes of production or products of single production which are carried out for the purpose of the decision of a question of expediency of statement of these products on production and (or) use to destination.

Finished products are subjected to the following tests.

**Qualification tests** – control tests of the installation series or the first industrial batch conducted to assess the readiness of the enterprise for the production of this type in a given volume.

**Predelivery tests** – control tests of products carried out by the technical control service of the manufacturer before presenting it for acceptance by the representative of the customer, the consumer or other receiving bodies.

**Acceptance tests** – control tests of production at acceptance control.

**Periodic tests** – the control tests of products which are carried out in volumes and in the terms established by normative and technical documentation for the purpose of control of stability of quality of production and possibility of continuation of its release.
**Inspection** – control tests of the established types of products which are carried out in the selective order for the purpose of control of stability of quality of production by specially authorized organizations.

**Typical tests** – control tests of products, conducted to assess the effectiveness and feasibility of changes to the design, formulation or process.

**Certification** – control tests of products carried out in order to establish compliance with the characteristics of its properties to national and (or) international standards.

**Laboratory tests** carried out in the laboratory.

**Bench tests** of the object, carried out on the test equipment (stand).

**Field tests** carried out at the testing area.

**Full-scale tests** of the object under conditions corresponding to the conditions of its use (actual conditions).

**Operational tests** carried out during operation (trial operation, controlled operation).

**Longitudinal** – a scientific method in which one and the same group of objects is studied during the time in which these objects have time to significantly change any of their significant features.

**Normal** – tests, methods and conditions of which provide obtaining the necessary amount of information about the characteristics of the properties of the object in the same time interval as provided in the operating conditions.

**Accelerated** – tests, methods and conditions of which provide obtaining the necessary amount of information about the characteristics of the properties of the object in a shorter time than under normal conditions.

**Short-time** – testing conducted on an abbreviated program.
1.2. Testing workbench

At present the majority of products produced by industry passes any bench control, both in single, and in mass production. Test benches are widely used for this purpose [1].

The test bench is the laboratory equipment which is intended for special, control, acceptance tests of various objects. Under these test objects are subjected to loads comparable to or exceeding loads in real conditions. The purpose of such tests is to determine the reaction of the object to the specific conditions and limit values of the load.

Structurally, the test bench is a combination of a working field (plate, frame or other device for fixing the tested device), a load subsystem of the sample (vibration, electrical or other depending on the type of test) and control and measuring equipment designed to write the parameters of the reaction of the sample to the load [2].

The control and measuring equipment includes various measuring instruments.

The measuring instrument – technical device, intended for measurement and which has standardized metrological characteristics, reproducing and (or) storing the unit of a physical quantity, the amount of which accept the same (within specified tolerance) for a certain time interval.

The law of the Russian Federation [3] defines the measuring instrument as the technical tool intended for measurements. The formal decision on reference of the technical means to measuring instruments is made by Federal Agency for technical regulation and metrology.

The requirements for product stability with respect to mechanical loads have been significantly tightened in recent years [4]. This is due to the increase in operational dynamic parameters such as speed and acceleration. Mechanical loads are the cause of deformation, wear and tear of the object. Vibration and shock
loads have the greatest negative impact. In addition, it is necessary to take into account the fact that in real conditions there is a complex load: harmonic vibrations can be superimposed random fluctuations. These processes complicate the design of test benches and the test process itself.

Complex test benches work together with the automated control systems of bench tests that allows to increase degree of reliability of tests, to reduce duration and labor input of tests, to increase labor productivity.

The increase in the volume of tests and the complexity of their implementation leads to the need for automation of test and measurement operations.

Usually the automated testing system is defined as the interrelated hardware and software, in which the control of the technological process of testing is automated. Such a system is essentially an information-measuring system.

The introduction of an automated test system leads to a change in the technology of data collection and processing during the tests. The new technology improves the accuracy of the test results, reduces the time of their conduct.

1.3. Testing workbench classification

In order to understand what type of dynamometer stands can be considered developing one, it is necessary to consider the classification of test benches for a number of features:

1) by tested object type:
   a. individual parts, components, assemblies,
   b. complete machines and devices;

2) by acquired characteristics type:
   a. static characteristics,
   b. dynamical characteristics;
3) by the uniqueness of the bench:
   a. universal,
   b. unique;
4) by the integrity of the tested object:
   a. with destruction,
   b. with deformation,
   c. without destruction;
5) by the type of tested material properties:
   a. structural;
   b. fatigue;
   c. vibration;
   d. wear test.
6) by the type of acquired physical characteristics:
   a. mechanical,
   b. climatic,
   c. thermal,
   d. radiation,
   e. electric,
   f. electromagnetic,
   g. magnetic,
   h. chemical.
7) by the automation level:
   a. non-automatic (manual),
   b. semiautomatic (automated),
   c. automatic.
1.3.1. Groups of test benches for obtaining the dynamometric characteristics

Test benches for obtaining dynamometric characteristics by the nature of the measured force (moment of force) can be divided into:

- dynamometer stands;
- equipment for testing properties of materials (tensile testing machine, installation for compression tests);
- devices for removal of traction characteristics of the electromagnet.

Various types of dynamometer sensors can be used as a sensing element in such stands:

- Mechanical
  There are two types of mechanical dynamometers: spring and lever. In a spring dynamometer, the force or torque is transmitted to the spring, which is compressed or stretched depending on the direction of the force. The value of the elastic deformation of the spring is proportional to the force of impact and is recorded. In the lever of the dynamometer, the force deforms the lever, the deflection of which is registered after

- Hydraulic
  The action of the hydraulic dynamometer is based on the displacement of the measured force of the liquid from the cylinder. Under the pressure of the fluid supplied through the pipe to the registered device.

- Electric
  The electric dynamometer consists of two components. The first converts the strain of force into an electrical signal, and the second amplifies and records the electrical signal of the first sensor. Inductive, piezoelectric resistance sensors and strain gauges are used to convert the force or moment of force into deformation. Under the action of force, the sensor is deformed, and the resistance bridge
currents change. The strength of the electrical signal is directly proportional to the deformation of the element and the resulting force of impact.

1.3.2. Division of dynamometric test benches by the type of test object

Now let's consider the division of dynamometer stands on the object of measurement.

1) **Motor stands.** Stand, where engine of the car is installed, belongs to the class of motor stands. We will refer to this class also any stands on which any power unit is installed, extracted from the design in which it operates in normal mode (as an internal combustion engine, dismantled from the car). To power units it is possible to carry both the motor, and the brake, the loading device, the electric car working in the motor or generator mode.

2) **Chassis bench.** The stands on which the whole vehicle is tested belong to a different class. The closest Russian-speaking established in the automotive and auto-repair industry term - "wheel bench". Wheeled these stands are called because the vehicles are based on their wheels.

   According to the type of device that forms a moving bearing surface, chassis benches are often also called drum (roller) benches, as they are most often used as a support surface cylindrical roller (rollers). In the field of rail testing, the term "roller" is used primarily to refer to the same concept. A division, however, should be distinguished from the few installations intended only for vehicles fitted with pneumatic tyres in which the moving support surface is formed by a closed-loop "treadmill". In tape stands tracks or closed strips of elastic material (for example, stainless steel) are used.

   The advantage of the tape benches is that the strained tapes form a flat supporting surface that models the surface coating in a better way than the cylindrical surface. Complex technologies of production of tapes lead to the high
price and rare application. According to the definition proposed by us, tape stands belong to the class chassis bench, but due to their extremely rare use of the concept of drum (roller) stand and chassis bench are almost identical.

The division of chassis benches by the type of design of bearing surface is illustrated with a Figure 1.1.

![Figure 1.1](image)

**Figure 1.1 – Schemes of designing of drum (roller) and tape bearing surfaces**

Figure 1.1 shows the elements of the stand forming the bearing surface, with the wheels of the tested samples installed on them (the vehicles themselves are not shown). The top row shows the top view and the bottom view contains the system view.

Figure 1.1a shows a roller bearing surface formed by two rollers whose length is not less than the width of the wheelbase of the vehicle under test. The system view of this scheme coincides with the system view of figure 1.1b. Both wheels of the same axle are supported by rollers, with each wheel touching two rollers at the same time.

Figure 1.1b shows a roller bearing surface formed by four short rollers whose length is such that each wheel rests on its own pair of rollers.

Figure 1.1c shows the drum bearing surface formed by two short reels, the length of which is such that each wheel of the axle rests on its (one) drum. It is also
possible to design a single long drum, the length of which is such that it rests on both wheels of the same axle.

Figure 1.1d shows a tape bearing surface formed by two narrow, closed tapes stretched over two rollers each. Each wheel of the test vehicle shall be supported by its own (one) belt.

As can be seen from the description to figure 1.1, in the field of automotive dynamometers, the diameter of the cylindrical support element defines the term applicable to it. So, the element of larger diameter, as a rule, is called a drum, and smaller – a roller.

Consider variants of trucks with different traction wheel schemes on some race bearing surfaces, presented by advertising materials of Taylor Co [5]. The race bearing surfaces shown in figures 1.2 and 1.3 are formed according to some schemes shown in Figure 1.1 or derived from them.

Figure 1.2 – Stands supporting schemes with reels 915 mm diameter and the distance between the axes of the reels for three-axis machines from 1219 to 1880 mm

Figure 1.3 – Supporting schemes of stands
At a certain distance between the wheels corresponding to the vehicle wheels radius, for example, stands with drums of 610 mm diameter and distance between axes for three-axis machines from 1219 to 1676 mm, shown on Figure 1.3, the paired drums ensure a stable position of the vehicle during the tests, a minimum resistance to the rotation of the wheels and an acceptable implementation of the traction force (Figure 1.3). For positioning and removing the car from the stand, the treadmills are equipped with brakes and lifts located between the drums. Along the length of the roller performs either short, separate for each wheel, or a long, continuous under both wheels of the axle. Usually one of drums (or one row) connect with brake or flywheels, another – with the speed meter of movement of the car. To improve the simulation of the interaction of wheels with the road on the stands sometimes use one large-diameter drum or create treadmills in the form of a continuous conveyor belt for each driving wheel. Such support devices require fixing the car on the stand, and so far have not been widely used in the diagnosis. The race bearing surfaces should have enough grip with the tires of the vehicle for transmitting tractive effort.

3) **Direct drive benches.**

Stands with direct drive, which is a small class, occupy an intermediate position between the motor and wheel stands. The car without wheels is set on the direct drive benches, and the shafts of load devices are attached directly to the wheel hubs.

The most obvious difference between a bench with a direct drive to the wheel hub from a conventional drum stand is the elimination of the tire transmitting the force to the load device. Instead of the bus, a special adapter (adapter coupling, figure 1.4) is used, which provides direct transmission to the power unit.
To carry out the tests, the wheels are removed from the test vehicle, the load block is directly attached to the wheel hub of the vehicle by the adapter.

This design eliminates the possibility of lateral tire deflection during testing, and the risk that the car will come off the bench at high speed. Tire temperature, pressure, clutch, etc., are variables that change not only from movement to movement, but also during the movement itself and make the measurement error. Stands with direct drive are deprived of these disadvantages.

Another advantage of the stands with direct drive in front of the drum stands is the absence of fastening belts used on the drum stands to fix the car. Fastening belts have uncertain and unstable deformation, and their tension depends on the nature of the tire loading, and, therefore, the coupling force and rolling resistance.

Another difference is the magnitude of the moment of inertia. Wheels, tires and drums have great inertia. This does not make it possible to track fast-changing processes, accurate power curve. The flywheel smooths out the response, not giving the full picture.

Stands with direct drive provide higher dynamics and recently have become widespread and are represented by models of a number of firms.
1.3.3. Division of dynamometer test benches into subclasses according to the type of load device

Dynamometer benches by type of load device are divided into inertial and power (another term – load). This separation does not impose any restrictions on their belonging to the classes corresponding to the composition of the tested samples. Therefore, the following description wheeled stands can equally be applied to the motor and to the stands with direct drive.

1) **The inertial benches.** Benches in which the inertial load of power units of the test sample is generated by the inertia of the connected rotating masses. Due to the simplicity and low cost of construction, such stands have gained the widest distribution.

Inertia stand is a spatial structure on which the tested vehicle is installed. On the frame axis, rotate freely one or more massive metal drums. The number of drums depends on the area of application of the stand, the schemes of paired and unpaired drums and the characteristics of the test sample - the number of axes, driving wheels, etc.

The advantages of the inertial bench: the simplicity (and low cost) construction, ease of calibration, possibility of calculating the friction losses in the transmission, the possibility of assessing the quality of build or the degree of engine run-in.

The shortcomings of the inertia of the stand: the lack of work in static mode (for constant speed, torque), the low accuracy of measurement of small ratio of inertia of the stand to the power of the engine (due to a small time promotion).

Inertia stands measure the time, path or the acceleration of the drums acceleration in a predetermined speed interval. Traction characteristics of the car can be obtained as a function of the angular velocity of rotation of the masses of the stand and the reactive moment of inertia that occurs when the car accelerates on it in series on all gears. As diagnostic parameters instead of power can be used,
therefore, time, path and acceleration or traction force. Stand setting to the appropriate power can be carried out by changing the set of attached rotating masses.

2) **Load bench and its loading devices.** Power (or load) bench is a structure similar to the inertial bench, the difference is that the drums have a lower mass, and "brakes" the drum is a special controlled device. It can be electric, hydraulic or friction. The computer control system is designed in such a way as to force the vehicle engine to operate at constant speed at certain throttle openings. Such a static mode of operation with the engine allows you to fine-tune the power system and ignition, to study the processes occurring in the motor.

Load devices of the load benches perform in the form of mechanical, hydraulic or electric brakes. Mechanical loading device is a disk (or block) brake. The disc is connected to one of the drums, the pads are fixed to the swinging brake rack, at a deviation of which the strain gauge indirectly measures the value of the brake torque of the stand, and, therefore, the traction torque on the wheels of the car.

The hydraulic brake of sufficient capacity has a compact size and can be placed in one of the drums of the stand. Typically, the load change is provided by the regulation of water supply or other, recycled, working fluid, and the torque is determined by the deviation of the stator reactive torque. Dynamometers with hydro-brakes are well suited to testing both stable and transient regime and has a low purchase price, low technical maintenance and reliability. The power generated by the engine is absorbed by turbulence and so called reactive back pressure caused by a special configuration of the interacting surfaces of the rotor and stator. The higher the flow rate of the working fluid passing through the dynamometer, the stronger the braking force or load. Bright representatives of such stands are hydraulic dynamometers of Taylor Dynamometer company.

As electric load devices is used by the devices based on the effects of eddy currents, inductive brake and power generators. The use of electric generators is
the most promising, because it provides a very high dynamics, flexibility and ease of management. In addition, the use of a reversible electric machine as a powertrain of this type of stands, which should become widespread in the future, allows not only to brake, but also vice versa, to rotate the engine of the tested vehicle through the transmission. At present, more stringent emission standards are being introduced, and manufacturers are forced to bring the settings of internal combustion engines to perfection. Not only power modes are investigated, but also such, as, for example, the movement of the vehicle coasting with a closed throttle (forced idle mode or engine braking). It is this mode can be simulated on the stand with the possibility of reverse promotion of the internal combustion engine. Thus, you set the exhaust gas recirculation (EGR), selected the ignition timing at idle run, the time of switching the fuel supply for a confident transition to engine idling, adjusts the valve operation the idle speed, etc.

Advantages of load stands: obtaining accurate results in the entire range of power and torque, which is designed to stand the possibility of "hot" running the engine.

Disadvantages of load stands: complex design, size, cost, the need to disperse the energy generated by braking the engine, the complexity of measuring friction losses.

3) Measuring device of the traction characteristics of the electromagnet.

This type of device is much less known than dynamometer stands or material property testers, but it is a separate type of device.

On the one hand, the unit is a motor chassis dynamometer, because the stand is installed on the power part of the electromagnetic drive (EMD) and removed traction characteristics of the drive.

On the other hand, the stand allows to obtain static characteristics from the private dynamic mode, which brings the device closer to the type of breaking machines.
Figure 1.5 shows the structure diagram of the device for obtaining the pulling characteristics of the electromagnet, where: 1 – power supply, 2 – electric drive, 3 – rotary motion to the linear converter screw-nut type, 4 – tested electromagnet, 5 – current sensor, 6 – power amplifier, 7 – line voltage generator, 8 – voltage rise time detector, 9 – voltage rise value indicator, 10 – load cell, 11 – motion sensor, 12 – maximum voltage indicator, 13 – time sensor, 14 – control and information processing unit, 15 – information display device.

As we can see on the figure 1.5 screw-nut block converts rotation of unspecified electric drive to the linear motion of the solenoid core. Pulling force is getting from the load cell and then unamplified signal is parsing in the control unit.
1.4. Dynamometric structures. Dynamometric design of the stands for obtaining the power characteristics of the vehicles

The dynamometer tests enable the characteristics of the vehicle to be determined by measuring and recording the performance of the vehicle [6]. Automotive dynamometer benches have a certain dynamometer structure, providing the dynamometer performance of the tested equipment, such as pulling force. In some cases, it is possible to measure not only pulling, but also the braking force developed by the tested sample. In most cases, such tests are limited to measuring the moment of force. To date, the measurement of the moment of force is carried out using tensometric, optical and inductive load sensors [7]. In Russia, when solving the problems of torque measurement, the equipment of foreign manufacturers (HBM (Germany), Kyowa (Japan), Dacell (Korea) and a number of others) is mainly used [8].

Analysis of different dynamometric benches allows to distinguish several groups of measurement systems, discussed in detail below.

1.4.1. Balance suspended stator

The system with the balance suspended stator of the energy converter (load device) shaft rotation is the most common in the market dynamometer products and is designed to measure the torque. The principle of operation of such a system is well illustrated by drawings of motor dynamometer stands developed in ETU, presented in figures 1.6, 1.7.
Figure 1.6 – Motor torque stand, operating in rotation mode. System view and top view.

On the Figure 1.6 following parts are designated: 1 – the tested engine, 2 – the load device (in this case – the electric machine), 3 – the frame of the stand, 4 – bearing supports, 5 – the system of measuring the reactive torque on the balance-suspended stator of the load motor.

From the system view in figure 1.6 it can be seen that the stator of the load machine 2 rests on the axles of the bearing supports and would have freedom of rotation around its axis, if not for mechanical connection, which includes a measurement system 5 (figure 1.7). The sensing element, which is the basis of the measuring system, is usually a tensometric load cell (in this particular case – S-shaped load cell S2-200N).

On the Figure 1.6 following parts are designated: 2 – load reversible electric machine, 3 – stand frame, 5 – system for measuring the reaction torque to balance the suspended load of the motor stator, comprising a force measuring sensor S2-200N.
Figure 1.7 – Motor torque stand, operating in rotation mode. View A from figure 1.6.

Examples of stands in which the dynamometer structure balance suspended stator is clearly visible are motor stands.

Figure 1.8 – Self-cooling dynamometer with eddy current absorber of Tianjin Tianbokeda Science & Technology Co., Ltd, China [9]

Figure 1.9 – Dynamometer bench of AvtoVAZ company, 1970-ss [10]

Engine dynamometric bench of Tianbokeda Tianjin Science & Technology Co., Ltd (figure 1.8) contains a spring-reading device with an arrow scale, performing the function of a sensing element and an indicator device. As the loading device in the stand applied the induction brake is mounted on the plate, one side of which rests on the hinges of rotation, and the other is suspended from a
hanger rack frame by means of a measuring and indicating device. As stated by the manufacturer, this "simple adjustable induction dynamometer implements a completely new concept of dynamic loading for precise testing of electric motors and other rotating devices and motors".

Power range within this stand is 0,18...55 kW, maximum torque 370 Nm, maximum speed of 2000 rpm. Induction brake of this stand is self-cooling; speed sensor – tacho with digital display; sensor and indicator – spring loaded-reading device. The small electric machine shown in the figure on the right is a test sample. The shafts of the test and load machines are connected by a coupling containing an elastic element that compensates for misalignment resulting from the error of installation and deflection of the induction brake stator during deformation of the sensing element of the measuring system under the influence of the developed moment.

Motor dynamometric bench of AvtoVAZ (figure 1.9) as a reading and indicator device contains station scales for luggage and hand luggage with a dial scale. As the loading device in this stand the electric machine is applied, which stator is established by right paws on the motionless support allowing rotation of the stator in small limits around the axis passing through right paws, and left – on scales. The internal combustion engine (figure 1.9 in the foreground) is the test sample. The shafts of the tested and load machines are connected by a cardan shaft, a closed casing, compensating for misalignment resulting from installation error, vibrations and deflection of the stator of the electric machine when the platform scales under the influence of the developed moment.

Examples of stands based on the dynamometer structure "balance suspended stator", except those shown above, are also all stands manufactured by Taylor, as well as many others.
1.4.2. Torque sensor

The torque sensor is usually installed between the drive shafts and the load and ensures the transmission of rotational motion. Torque sensors are widely used in dynamometer products and compete with systems with a balance suspended stator. Torque sensor in the classical implementation is a rotor rotating freely in the stator and having a shaft, output on both sides and where integrated inductive current rotation frequency sensor 1 (figure 1.10). Often, the torque sensor is combined with a speed sensor in order not to install an additional separate device.

Figure 1.10 – The torque sensor DacellTRB with a shaft of circular cross-section with two sides with keyways.

Figure 1.10 shows a torque sensor Dacell Co TRB designed to measure torque on a continuous rotating elements. Platinized contact provides stability and accuracy of measurements. This model is most suitable for industrial measurements, in particular when testing engines and transmissions of cars. Optionally, the TRB can be equipped with an integrated inductive type speed sensor.
Figure 1.11 – A torque sensor with a stator without bearings and shaft with a cross section in the form of external and internal hexagon of Burster Praeziisionsmesstechnik GmbH&co kg, Germany.

Torque sensors are designed for a variety of moments (up to 2 MNm [11], figure 1.12) and speed: from 0 – as static torque sensors designed to measure torsional moments without rotating the system, for example, in torque wrenches – up to, for example, 25000 rpm (when using current collectors, in particular).

Figure 1.12 – Large nominal torque sensor.

Torque sensors are available in different types – with fixed stator and with a stator, suspended on a shaft (not having other, except the bearings, the points of support; with cable and radio broadcast; with a shaft with a cross section in the
form of a circle, the internal and external square or hexagon, with a keyway or without; with the rotor, instead of having a shaft on one or both sides of the flange (figure 1.13) for the connection with mating parts, and may also represent virtually any combination of the following traits, convenient for specific design applications.

Figure 1.13 – Static torque sensor, Dacell TCN16 with a flange on one side and a circular shaft with a keyway on the other.

Torque sensors are used in automotive dynamometer benches containing drums, treadmills, motor stands and direct drive benches. It is obvious that the use of torque sensors is impossible on the benches based on the simulation path through a straight cut. On such stands the dynamometer structure direct measurement of force is realized.

1.4.3. Direct measuring of force

Among the dynamometer benches it is possible to distinguish a group of structures that provide a direct measurement of the traction force developed by the tested sample. As a sensing element in such constructions, devices described in the paragraph "Balance suspended stator" – tensometric and spring are used.

The principle of operation of such a structure illustrates the design shown in figure 1.14, where next parts are designated: 22 – straight cut rail, 25, 26 – spring
that provides oscillatory reciprocating motion of the rail, 29 – longitudinal force torque sensor of "strain gauge" type, 30 – wheel.

In this design, the wheel in contact with the rail is rotated. On the rail the result is the effect of a longitudinal force that moves it, and measured by the force sensor "massdot" 29.

![Figure 1.14 – Stand for the study of the wheel-rail system.](image)

The calibration platform for the friction coefficient measurer «IKS-1», produced in the ETU has exactly the same dynamometric structure.

![Figure 1.15 – Calibration platform, manufactured in ETU.](image)

Figure 1.15 shows the wheel chassis dynamometer manufactured in ETU. Covering platform simulator 1 has the freedom to move on the guide rollers. The horizontal force generated in this case is measured with the S-shaped tensometric load cell 2.

Implementation of the structure "direct measurement of force" is possible not only on the stands with a straight segment of the path. A similar measurement is possible on stands based on tapes or drums, if the structural element containing
the path simulator has the freedom of movement under the influence of the traction force, limited by the sensor measuring the traction force.

If the drum has the freedom not of translational movement, but the element that carries it, under the influence of the measured traction force rotates around a certain axis different from the axis of the drum, such a construction is difficult to classify unambiguously, and it partially satisfies the characteristics of the group described in paragraph "Balanced suspended stator". Thus it turns out that the boundary of the groups described in the "balanced suspended stator" and "direct force measurement" points is blurred. If you want you can allocate a small transition group.

1.4.4. Inertial dynamometric structure

The inertial benches have inertial dynamometric structure, devoid of any force measuring elements. Determination of the moment in these stands is carried out by calculating on the basis of knowledge of the moment of inertia of the rotating reduced masses and measuring the acceleration/deceleration time or the rotation angle from one threshold value of the rotational speed to another. Usually these stands are equipped only with a speed sensor and a clock.

The system is very simple and reliable and is widely used in cheap car and motorcycle as well as railway dynamometer stands.

1.4.5. Indirect determination of the torque by measuring the tension of the chain or belt

To date, the implementation of such a dynamometric structure is found only in one chassis dynamometer – manufactured in ETU the maintenance stand for the
friction coefficient measurer. This type of measurement is possible in devices using cord, belt or chain transmission.

1.4.6. Determination of the torque by the current

The measurement of the braking torque or thrust torque in the electromechanical dynamometric structure allows, with high accuracy, measure the true values of the unknown quantities, especially in the case of the experimental method. In the case of the analytical method permissible systematic errors within ±1% of the measured value, and in the experimental method can provide a higher accuracy of measurement. But it is important to note that in both methods, the electromechanical method of dynamometry provides the same accuracy of reproduction (repeatability) of the measurement results at the same state of the path simulator surface, reaching values not worse than ±0,5%.

Determination of the torque by the current with different accuracy is realized by different manufacturers for different types of engines. Thus, the company ABB in its technology direct torque control (DTC) provide torque determination of the asynchronous motor with an accuracy of 1% [12].

Summary: in this chapter an analysis of the existing types of dynamometric benches was carried out. Based on this analysis, testing bench classification based on different criterions was offered.
2. THE DESIGN OF THE CALIBRATION PLATFORM

In accordance with the requirements of the automated platform for calibration of the friction coefficient meters, it is necessary to develop a mechanical design of the stand and select the necessary components.

2.1. Bench mechanical design development

For a more accurate understanding of the functional purpose and capabilities of the stand the principle of its operation is described below.

2.1.1. Principle of operation

Electromechanical friction coefficient measurer (EMFCM) calibration is carried out on the stand, which provides measurement and setting of the longitudinal shear force at the point of contact with the surface of the measurement wheel of the platform, as well as the measurement of the measurement wheel normal pressure on the surface. Loading of the S-shaped tensometric load cell is ensured by linear movement of the screw inside the nut fixed to the platform body by means of a stepper motor.


Initially, the design of the stand looked as shown in figure 2.1.
The measuring wheel of the friction coefficient meter is installed on the plate 18. As a result of the rotation of the nut 13 screw 9 moves linearly. The data is taken from the beam-type load cell 33 and the S-shaped load cell 32.

Figure 2.1 – Outline drawing.

The component of the transformation of the rotational into translational motion is shown in figure 2.2. The picture shows: 9 – screw, 10 – plate, 11 – bushing, 12 – ring, 13 – nut, 15 – body, 16 – bar, 24 – screw M8, 26 – nut M8, 28 – pin, 29 – cable.

Figure 2.2 – Bench segment
To perform the tasks you need to make a node, shown in figure 2.3. The manufacturing of this part will require cutting, bending, drilling operations.

Figure 2.3 – The support of the stepper motor. 34 – adapter bit, 35 – coupling, 36 – stepper motor.

The result is a mechanical design shown in figure 2.4.

Figure 2.4 – Drawing of the platform with an attached stepper motor.
The developed scheme slightly extends the original design, which, however, does not affect on transportation, since this unit is removable. In addition, the usability of the stand significantly increased, since the operator now does not have to be directly next to the friction coefficient measurer during the calibration procedure.


Figure 2.5 shows the assembly drawing of the calibration platform for the friction coefficient meter.

The main difference from the design shown in figure 2.1 is that the nut 33 is rigidly fixed to the platform body, the screw 13 moves horizontally and protrudes to the nut, which slightly complicates the installation of the engine, however, simplifies the design itself, since the node converting rotational motion into translational motion has now become easier.

Figure 2.5 – Outline drawing.
In addition, the movable plate 6 has the freedom of movement only in the horizontal axis, which increases the reliability of the stand. Due to the use of modern methods of processing of materials it was possible to facilitate the construction, maintaining its rigidity.

The size of the working stroke is preserved and is 100 mm.

Figure 2.6 shows a drawing of the stand with an attached stepper motor. Since the stepper motor is attached to the screw, which has the freedom of linear movement, it is necessary to lay in the design of the freedom of linear movement of the stepper motor in a horizontal direction. To fulfill this requirement, the stepper motor is fixed to the rails, which do not allow the engine to crank around its own axis, thereby ensuring the efficiency of the stand.

![Figure 2.6 – Drawing of the platform with an attached stepper motor.](image)

The main difference of the given constructions in the given problem is in the component of transformation of rotational motion into translational motion. In the first version of the platform, the screw went inside the nut during rotation, which allowed the motor to be rigidly fixed to the platform body. In the second version, this approach is not feasible, so it is necessary to provide for the installation of guides on which the stepper motor will move as a result of the linear movement of the screw during the stand operation.
2.2. Stand components selection

In accordance with the master’s thesis task, it is necessary to choose power supplies and fitting elements of the bench. Figure 2.7 shows a simplified functional diagram of the stand, which also shows the types of relationships between elements.

A solid black arrow indicates a power line, a contour arrow indicates a data line, and a broken line indicates a direct mechanical link.
2.2.1. Stepper motor selection

The main criterion for choosing a stepper motor is the torque developed by it. The parameters stated in the master’s thesis task meet stepper motor FL86STH118-4208A, shown in figure 2.8.

![Figure 2.8 – Stepper motor FL86STH118-4208A.](image)

Some of its parameters are given in Table 2.1.

Table 2.1 – Motor main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>FL86STH118-4208A</td>
</tr>
<tr>
<td>Phase current, A</td>
<td>4,2</td>
</tr>
<tr>
<td>Phase resistance, Ohm</td>
<td>0,9</td>
</tr>
<tr>
<td>Phase inductance, mH</td>
<td>6</td>
</tr>
<tr>
<td>Torque, kg*cm</td>
<td>87</td>
</tr>
<tr>
<td>Length, mm</td>
<td>118</td>
</tr>
<tr>
<td>Rotor inertia, g<em>cm</em>cm</td>
<td>2700</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>3,8</td>
</tr>
</tbody>
</table>
Motor torque assurance coefficient is assumed to be 2, because of variable value of friction force in screw-nut.

2.2.2. Stepper motor driver selection

Driver SMD-4.2 was selected to control the stepper motor. Driver is shown in figure 2.9.

![Figure 2.9 – Stepper driver.](image)

Stepper motor driver SMD-4.2 is designed to control two-and four-phase hybrid stepper motors with phase currents up to 4.2 A [13].

The unit provides high accuracy, speed and low vibration.

The unit uses differential inputs to improve noise immunity and interface flexibility. The interface allows to receive unidirectional control signals from the controller.

Stabilized and non-stabilized DC power supplies can be used to power the unit. Several units with one power supply can be used to reduce the total cost.

The unit allows you to split the step until the 1/16.

It is possible to set the holding current (half/full from the value of the operating current).

Stepper motor control mode:
- Control of the stepper motor from an external device by means of logical signals: “STEP”, “DIRECTION” and “RESOLUTION”.
- Signaling is carried out by pulses.

### 2.2.3. Driver supply unit

As a power supply for the stepper motor driver in order for the bench to be independent of the measurement object parameters, an additional power supply must be used for the stepper motor driver.

The H1000S24 shown in figure 2.10 is used as such power supply.

![Power supply block](image)

Figure 2.10 – Power supply block.

Stabilized, unregulated power supply H1000S24 is designed to convert mains voltage 220VAC 50Hz to a stabilized voltage 24VDC.

The proposed DC power supply consists of a power transformer, stabilizers and electronic protection circuits. On the front panel of the unit there are terminals for connecting the load and mains voltage 220V.

The power supply is used to power DC drives: collector motors, stepper drives, brushless motors, as well as for other drives and devices.
The power supply has an electronic circuit protection against overload, short circuit and high voltage.

Power supply main characteristics are listed in table 2.2.

Table 2.2 – Power supply block parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage, V</td>
<td>24</td>
</tr>
<tr>
<td>Output current, A</td>
<td>42</td>
</tr>
<tr>
<td>Power, W</td>
<td>1000</td>
</tr>
<tr>
<td>Input voltage, VAC</td>
<td>176~264</td>
</tr>
<tr>
<td>Protection features:</td>
<td></td>
</tr>
<tr>
<td>Overvoltage protection, V</td>
<td>&lt; 17</td>
</tr>
<tr>
<td>Short-circuit protection</td>
<td>Automatic recovery</td>
</tr>
<tr>
<td>Overcurrent protection</td>
<td>150~200%</td>
</tr>
<tr>
<td>Breakdown strength:</td>
<td></td>
</tr>
<tr>
<td>Between primary and secondary circuits, VAC during 60 s</td>
<td>1500</td>
</tr>
<tr>
<td>Between primary circuit and ground, VAC during 60 s</td>
<td>1500</td>
</tr>
<tr>
<td>Between secondary circuit and ground, VDC during 60 s</td>
<td>500</td>
</tr>
<tr>
<td>Insulation resistance:</td>
<td></td>
</tr>
<tr>
<td>Between primary and secondary circuits, MOhm</td>
<td>50</td>
</tr>
<tr>
<td>Between primary circuit and ground, MOhm</td>
<td>50</td>
</tr>
<tr>
<td>Between secondary circuit and ground, MOhm</td>
<td>50</td>
</tr>
<tr>
<td>Leak current, mA</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>
The power supply can be used to operate the:

- brushed motor geared DC;
- brushless motors;
- stepper motor drivers.

### 2.2.4. Weighing terminal selection

A weighing terminal must be used for information collecting, processing and transmitting from tensometric load cells. The parameters defined in the master’s thesis task, satisfies terminals URALVES KSK18 [14], shown in figure 2.11.

![Weighing terminal KSK18](image)

Figure 2.11 – Weighing terminal KSK18

The weighing terminal provides direct connection to the tensoresistor bridge sensors without additional coupling according to the standard 4-wire circuit (optional 6-wire circuit with autocompensation of losses at connection at a distance of more than 50 m). The terminal has a 6-digit led display, 8 status indicators,
control keyboard. It has the functions of manual setting of autozero, range of manual zero setting, autozero setting and digital filters, indicator stabilize weighing indicator zeroing, the net indicator, low battery indicator, battery indicator.

The adjustment of the terminal as part of the balance is made without external adjusting elements with the preservation of the setting codes in the storage device protected by from power failures, with the number of recording cycles – not less than 100000. Weighing terminal main parameters are listed in Table 2.3.

Table 2.3 – KSK18 main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC frequency, Hz</td>
<td>20</td>
</tr>
<tr>
<td>ADC bitness, bits</td>
<td>20</td>
</tr>
<tr>
<td>Sensibility, uV/div</td>
<td>1.5</td>
</tr>
<tr>
<td>Input signal range, mV</td>
<td>from -16 to 18</td>
</tr>
<tr>
<td>Load cell connection schema</td>
<td>4-, 6-wired</td>
</tr>
<tr>
<td>Number of connected load cells</td>
<td>Up to 6 pc. 350 Ohms each</td>
</tr>
<tr>
<td>PC interface</td>
<td>RS232</td>
</tr>
<tr>
<td>Indicators type</td>
<td>LED</td>
</tr>
<tr>
<td>Reccomended distance to the load cell, not more (connection schema)</td>
<td>up to 50m (4-wired); up to 100m (6-wired)</td>
</tr>
<tr>
<td>Load cell supply voltage, VDC</td>
<td>5</td>
</tr>
<tr>
<td>Supply voltage VAC, at frequency 50 (±1) Hz</td>
<td>from 187 to 242</td>
</tr>
<tr>
<td>Power consumption, W</td>
<td>less than 6</td>
</tr>
<tr>
<td>Battery</td>
<td>6V, 4.5Ah</td>
</tr>
<tr>
<td>Operating conditions:</td>
<td></td>
</tr>
<tr>
<td>- operating temperature range, °C</td>
<td>from 0 to +40</td>
</tr>
<tr>
<td>-relative humidity (max)</td>
<td>85%</td>
</tr>
</tbody>
</table>
It is important to notice that selected terminal has RS232 interface for data transmission.

### 2.2.5. Sensors selection

It is necessary to define the used tensometric load cells.

**S-type tensometric load cell.** The URALVES K-R-16K tensometric load cell shown in figure 2.12 satisfies the requirements.

![Figure 2.12 – Load cell K-R-16K.](image)

Load cell main parameters are listed in the Table 2.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum limit of measurement (MLM), kg</td>
<td>100</td>
</tr>
<tr>
<td>Operating transmission coefficient (OTC), mV/V</td>
<td>2±0,003</td>
</tr>
</tbody>
</table>
Ending of the Table 2.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy class (GOST 30129)</td>
<td>C3</td>
</tr>
<tr>
<td>Zero balance</td>
<td>±1%</td>
</tr>
<tr>
<td>Type of applied force</td>
<td>Tension / compression</td>
</tr>
<tr>
<td>Number of calibration intervals</td>
<td>3000</td>
</tr>
<tr>
<td>Temperature sensitivity drift, °C</td>
<td>±0.02%/10</td>
</tr>
<tr>
<td>Temperature zero drift, °C</td>
<td>±0.02%/10</td>
</tr>
<tr>
<td>Input resistance, Ω</td>
<td>400±20</td>
</tr>
<tr>
<td>Output resistance, Ω</td>
<td>352±3</td>
</tr>
<tr>
<td>Insulation resistance, MΩ</td>
<td>5000</td>
</tr>
<tr>
<td>Temperature compensation range, °C</td>
<td>-40...+50</td>
</tr>
<tr>
<td>Operating temperature range, °C</td>
<td>-40...+50</td>
</tr>
<tr>
<td>Maximum permissible load</td>
<td>125% of MLM</td>
</tr>
<tr>
<td>Ultimate load</td>
<td>200% of MLM</td>
</tr>
<tr>
<td>Recommended supply voltage, V</td>
<td>5...12</td>
</tr>
<tr>
<td>Maximum supply voltage, V</td>
<td>15</td>
</tr>
<tr>
<td>Protection class (GOST 14254)</td>
<td>IP67</td>
</tr>
<tr>
<td>Body material</td>
<td>Alloy steel</td>
</tr>
<tr>
<td>Cable diameter, mm</td>
<td>5</td>
</tr>
<tr>
<td>Cable length, m</td>
<td>3</td>
</tr>
</tbody>
</table>

**Beam type tensometric load cell.** The main parameters of the sensor, shown in figure 2.13, selection are the rated load and the height of the load cell.
URALVES K-10G load cell satisfies the specified parameters, the main parameters of which are given in table 2.5 [15].

Table 2.5 – K-10G parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum limit of measurement (MLM), kg</td>
<td>100</td>
</tr>
<tr>
<td>Operating transmission coefficient (OTC), mV/V</td>
<td>2±0,02</td>
</tr>
<tr>
<td>Accuracy class (GOST 30129)</td>
<td>C3</td>
</tr>
<tr>
<td>Zero balance</td>
<td>±1%</td>
</tr>
<tr>
<td>Type of applied force</td>
<td>Bound</td>
</tr>
<tr>
<td>Number of calibration intervals</td>
<td>3000</td>
</tr>
<tr>
<td>Temperature sensitivity drift, °C</td>
<td>±0,02%/10 °C</td>
</tr>
<tr>
<td>Temperature zero drift, °C</td>
<td>±0,02%/10 °C</td>
</tr>
<tr>
<td>Input resistance, Ω</td>
<td>404±15</td>
</tr>
<tr>
<td>Output resistance, Ω</td>
<td>350±3</td>
</tr>
<tr>
<td>Temperature compensation range, °C</td>
<td>-40...+50</td>
</tr>
<tr>
<td>Operating temperature range, °C</td>
<td>-40...+50</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Maximum permissible load</td>
<td>120% of MLM</td>
</tr>
<tr>
<td>Ultimate load</td>
<td>150% of MLM</td>
</tr>
<tr>
<td>Recommended supply voltage, V</td>
<td>5...12</td>
</tr>
<tr>
<td>Maximum supply voltage, V</td>
<td>15</td>
</tr>
<tr>
<td>Protection class (GOST 14254)</td>
<td>IP67</td>
</tr>
<tr>
<td>Body material</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>structural steel</td>
</tr>
<tr>
<td>SS</td>
<td>stainless steel</td>
</tr>
<tr>
<td>Cable diameter, mm</td>
<td>5</td>
</tr>
<tr>
<td>Cable length, m</td>
<td>5</td>
</tr>
</tbody>
</table>

Selected load cell will operate properly even at load force thrust or supply undervoltage.

### 2.2.6. Microcontroller selection

It follows from the analysis of the obtained structure of the stand that the microcontroller should perform the following functions:

- receive data from weighing terminals;
- send control signals to stepper motor driver;
- to interact with a computer through a COM/USB/Ethernet;
- provide testing of the recorded program.

These requirements are met, for example, ATmega32. 8-bit AVR microcontrollers with 32KB of programmable FLASH memory.
2.3. Control system design

The information-measuring system of the created test complex is the most important and universal part of it, as it performs the main task, namely computer processing of information in the most exhaustive and at the same time friendly enough form, convenient for studying [16], [17].

Information and measuring system of the created stand should provide:

1. Indication in preparation for the test of the following data:
   - power on;
   - dates, month numbers, two digits of the year, time of day in hours and minutes;

2. Current measurement of the pulling force applied to the load cells by the measuring wheel under test:
   - measurement, indication and documentation of the dependence of the pulling force on the distance with an accuracy of ±5% over the entire measuring range;

2.3.1. Application of state transition graphs in control system

The central concept of the proposed model of designing of control systems is an automaton object. An automaton object has much in common with a traditional finite state machine [18], but, at the same time, it has significant differences. Just like the finite state machine in the form of Miles, the automaton object is given by a state transition graph, where at each transition an event (the input action) that initiates this transition is indicated, and also the sentry condition of the transition can be indicated, and the effect (the output impact), produced as a result of the transition. We use the following model extensions, each of which outputs the proposed model of an automaton object from the class of finite automata:
• events are not single characters, but can have parameters and can bring an arbitrary amount of information to the automaton object;
• guard conditions can have arbitrary complexity and depend on the current values of an arbitrary number of local variables, and not only on the current state;
• effects are also not single characters, but can have parameters and can write in an external memory an arbitrary amount of information.

Let's consider a key figure for further exposition (Figure 2.14). On the left is a diagram of an automaton object combining the concepts of the state machine, components, ports, and interfaces of the unified modelling language (UML) [19]. The main innovation is that we think of a state machine encapsulated in a component, and explicitly specify the ports and interfaces through which the automaton object interacts with the outside world (Figure 2.14, a). On the right is a scheme of connections, traditional for control systems that react to external events [20]. At the middle level of the scheme, there is a control automaton. The input alphabet of the machine is the events sent by the event source. Depending on the events received and the results of checking the guard conditions on the transitions, the machine changes its current state and performs actions on transitions (effects) addressed to the control object. In the traditional scheme, control automata, event sources and control objects look like unequal and diverse objects. In the proposed model, event sources and control objects are also automaton objects, which is achieved by introducing the appropriate generalization relations (Figure 2.11, b).

The model of the automaton object (Figure 2.14, a) is constructed from the following considerations: in accordance with the Meyer principle [21], the operations of the interface of any object should be divided into queries delivering values and not changing the state of the object (the «request» stereotype), and commands that change the state of the object, but do not deliver values (the stereotype «command»). Further, considering the mandatory indication for each object not only of the provided but also required interfaces, we obtain exactly four
possible types of interfaces for interaction between objects: provided commands, and required commands, provided queries, and required queries. The list of combinations is exhaustive, and in this sense, the proposed model is final and perfect, since it takes into account all possible types of interaction of objects that satisfy the Meyer principle.

Applying this observation to automata, we obtain exactly four possible types of interfaces between the automaton, its source of events and the control object (Figure 2.14, a):

- events on the transitions of the machine are provided by the commands of the automaton, the arguments of the events, if any, initialize the local variables of the automaton;
- guard conditions on the transitions are logical expressions over the values that deliver the requested queries to the control object;
- effects are the required commands of the control object, as arguments can be passed the values of the local variables of the machine;
- the machine can provide queries about its current state and the values of other local variables.

We affirm that in practical cases it is more convenient from the decomposition considerations to describe the behavior not of a single automaton
object, but of a system of interacting automata objects. All automata objects in the system are equal, and each of them interacts with other automata objects and with the external environment through interfaces of four types (Figure 2.14, a). The source of events and the control object for a given automaton object can be either external objects, or the same, or another system automaton. Thus, event sources, control objects, control automata are all automaton objects, and event sources and control objects are no more than specialized interfaces (Figure 2.14, b). A unified interpretation of control automata, control objects and event sources as automata objects is the most important advantage of the proposed model [22].

Consider the application of the proposed approach to the design of the platform for the calibration of the friction coefficient meter (figure 2.15). As a result of the tests, it is necessary to obtain the dependence of the thrust force on the linear movement of the carriage.

Figure 2.15 – Automaton object “Controller”.

`\[\text{Diagram for the calibration platform for the friction coefficient meter.}\]`
The stand includes a computer on which the test management software and test results analysis software are running. The computer is connected to a controller that directly controls the equipment and carries out the measurements required in the tests. The equipment consists of a stepping motor that rotates the screw. Due to the rotation of the screw, the displacement \( L \) of the calibration platform carriage changes. On the rotational axis of the screw, between the screw and the test solenoid is a strain-gauge S-shaped sensor that determines the force \( F \) caused by the displacement measuring wheel. Naturally, the hardware has some parameters and tolerances that are considered to be known in advance. So, for the stepper motor, the minimum step size \( d_{\text{min}} \) is known which determines the accuracy of the displacement measurement, and the known speed \( v \) is known, which allows to determine the time required for the core displacement by a predetermined value. For the screw, the thread characteristics are known which allow one to determine the displacement \( L \) with a known accuracy from the angle of rotation of the screw and the maximum possible displacement \( L_{\text{max}} \) is known. For the sensor, the minimum measured force \( F_{\text{min}} \), determined by the sensitivity of the sensor, is known and the maximum measured force \( F_{\text{max}} \), at which the test should be stopped in order to avoid the destruction of the stand.

It is believed that the controller can execute the command \( \text{STEP}(d) \), where \( d_{\text{min}} \leq |d| \), where the value of \( d \) can be either positive or negative, since the screw can be rotated in both directions. The screw can respond to the \( \text{LENGTH}(L) \) query, that is, determine the current offset, and the load cell can respond to the request \( \text{FORCE}(F) \) by converting the resulting voltage difference in the arms of the strain gauge bridge.

The reliability of the control system is achieved by checking the execution time constraints. Time \( t_1 \) limits the waiting time for measurement results, \( t_2 \) – limits the time for shredding the step, \( t_3 \) – limits the waiting time for computer signals; \( t_4 \) – limits the time of the development of the command by a stepping motor.
2.3.2. Software functional requirements

The microcontroller program has to perform the following functions:

- control of the stepper motor according to the STEP/DIR protocol;
- supplying and receiving analog information from the load cell;
- supplying and receiving analog information from the linear displacement sensor;
- conversion of received analog signals into digital code;
- initial filtering of the received data;
- transmission of measurement results to the computer via UART Protocol;
- receiving control commands from a computer using the UART Protocol.

Separate item it must be specified that a computer with Windows OS, 2048MB RAM, USB ports, mouse, keyboard, display are using.

PC desktop application should:

- display the status of the stand (ON/OFF/MEASURING);
- plot the pulling force dependence on the core position
- write the received data to the table in the format DATE/TIME/FORCE/POSITION;
- contain controls START/STOP.

Summary: in this chapter the following element of design were implemented:

- mechanical construction, including two different versions of the bench,
- electric functional scheme,
- control program architecture.

All demands stated in the master’s thesis task were fulfilled.
3. THE METHODOLOGY OF THE TESTS

The methodology of EMFCM testing includes preparation for the calibration, calibration, determination of the radius of the measuring wheel, the definition of error of measurement of the coefficient of friction. These paragraphs are described in detail below.

3.1. Preparation for the EMFCM calibration

EMFCM calibration is carried out on the STAND, which provides measurement and setting of the longitudinal shear force at the point of contact of measuring wheel (MW) with the surface of the platform, as well as the measurement of the MW normal pressure on the surface.

Preparing for calibration involves the following steps:
- to raise MW to transport position using winches mounted on EMFCM;
- install (roll up) EMFCM on the supports (observe the upper and lower sides of the supports), so that the transport wheel (TW) was at a height of 90 mm (see Figure 3.1);
• install the STAND platform under the MW, observing the parallelism of the platform relative to EMFCM;

• fix the STAND under EMFCM using a special rod (pipe) to prevent its longitudinal movement;

• connect to the load cells URALVES K-10G and URALVES K-R-16K corresponding digital indicators type URALVES KSK18 and turn them ON (see Figure 3.2). If the indicator values are different from 0, reset them by long pressing (2 sec.) on the "ZERO" button;

![Figure 3.2 – Weighing terminal connection.](image)

• block MW from rotating forward (in the direction of movement of the EMFCM) using a special blocker, placing it as shown in figure 3.3;

![Figure 3.3 – MW rotation blocker.](image)
• lower the MW on the platform of the STAND. At the same time, the contact spot should be in the center of the platform plate of the STAND (see Figure 3.4);

![Image](image_url)

Figure 3.4 – Completing preparations for the calibration procedure.

• install the EMFCM in a horizontal position by rotating the upper handle of the support wheel (SW);

*Note. The horizontal position of the EMFCM is fixed at the level fixed to the suspension arm MW. The EMFCM is in the horizontal position if the level air bubble is in the middle between two black strips.*

• connect the control and display panel (CDP) to EMFCM and turn them on.

*Attention. The tyre pressures of MW and TW shall be 2.0 ± 0.2 kgf/cm² and 2.22 ± 0.22 kgf/cm², respectively.*
3.2. EMFCM calibration

Go to the section calibration on CDP to fill calibration tables containing the following columns:

- 1st column, "Force": the horizontal force in kilograms to which the measuring wheel must be loaded by the STAND platform;
- 2nd column, "Weight": the value of the normal force in kilograms measured by the STAND during calibration;
- 3rd column, "Mom.": EMFCM ADC indications with appropriate values of a tangent of a load with the passage calibration;
- 4th column without a name: the column Declaration variables $\Delta v$, $\Delta m$, $0v$ and $0m$;
- 5th column, "Tech": averaged values of the difference between the weight of the $\Delta v$ and the moment $\Delta m$, as well as calculated values of the weight $0v$ and the moment $0m$ at zero horizontal load on the MW, calculated for the current calibration recorded on the EMFCM controller;
- 6th column, "New": the averaged values of the difference between the weight of the $\Delta v$ and the moment $\Delta m$, as well as the calculated values of the weight $0v$ and the moment $0m$ at zero horizontal load on the MW, calculated for a new calibration, not yet recorded on the EMFCM controller.

Carrying out EMFCM calibration includes the following sequence of actions:

1) enter the value of MW radius in the input field of the MW radius (1 in figure 3.5), click on the "Save changes"(2 in figure 3.5);
2) go to the CDP calibration screen (Figure 3.6);

Figure 3.5 – CDP settings screen.

Figure 3.6 – CDP calibration screen.
3) by rotating the platform tension disc, load the S-shaped load cell with a force of 10 kg (according to the column of the calibration table Figure 4.6, a), press the "Next" button (Figure 3.6, j);

4) enter the value of the normal load in the Weight field (Figure 3.6, f) on the CDP screen and press the Next button on the CDP screen. After that, in the "Weight" field (Figure 3.6, b) in the calibration table, the entered weight value will appear on the CDP screen, and in the "Moment" field (Figure 3.6, c) in the calibration table, the value from the EMFCM ADC will appear on the CDP screen under these MW loading conditions;

5) do items 3) and 4), increasing the tangential force to 20 and 30 kg, and thus fill 2 and 3 columns to half (Figure 3.5);

<table>
<thead>
<tr>
<th>Сила</th>
<th>Вес</th>
<th>Мом.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10т</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20т</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30т</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3.7 – Loading indications in one direction.

6) increase in the tangent force of up to 35 kg;

**Do not press “Next” button.**

7) execute items 3) and 4), easing the tangential load to the values 30, 20, 10 kg, and thus fill 2 and 3 columns of the calibration table to the end;

8) compare the values of the columns "Tek" (Figure 3.6, d) and "New" (Figure 3.6, e), determine the departure of the EMFCM readings compared with the previous calibration. If the calibration results are satisfactory, press the "Accept" button (Figure 3.6, i). Thus, the current calibration results will be recorded on the EMFCM controller;

**Important note.** *If the “Accept” button was not pressed or the “Cancel” button (Figure 3.6, l) was pressed, the current calibration parameters will not save when you exit the calibration window.*

9) exit the calibration mode.
**Attention.** During calibration, it is allowed to rotate the platform tension disc only in the direction of increasing the load (clockwise) when filling the upper half 2 and 3 columns of the calibration table and only in the direction of decreasing (counterclockwise) when filling the lower half 2 and 3 columns of the calibration table. Values on the screen of the indicator type KSK18, connected to the S-shaped load cell, at the time of pressing the "Next" should not quickly decrease (increase). It is necessary to achieve the speed of changing the indicator readings, not more than about 0.01 kg per second.

Achieving the desired tangential force value by repeatedly reducing and increasing the load is not allowed, as in this case, the dry friction moment makes an error in the calibration values. Therefore, if during calibration it is necessary to load (when moving in the direction of increasing the load) or unload (when moving in the direction of reducing the load) the S-type load cell, exceeding (smaller), than it is necessary at this stage, it is necessary to completely remove the load from the S-type load cell and repeat the entire calibration procedure again.

### 3.3. Measurement of the current radius of the EMFCM measuring wheel

To measure the current radius of MW $R_{MW}$ (with deformed pneumatics caused by the force of the normal load on the measuring wheel, at a pressure in pneumatics equal to $2 \pm 0.2$ kgf/cm2), the following operations must be performed:

1) install the ruler on the floor near the MW;
2) measure the height of the platform $h$ with a ruler with abrasive coating;
3) measure the height from the floor to the top of the MW hub bearing cover $H$;
4) calculate $R_{MW}$ in a fixed angular position by the formula:

$$R_{MW} = H - h - r_{HB},$$

where $r_{HB} = 40$ mm is the radius of the MW hub bearing cap.
3.4. Determination of the friction coefficient measurement error

The determination of EMFCM FC measurement error includes the following sequence of actions:

1) to calibrate EMFCM according to p.2;
2) repeat the EMFCM calibration procedure 12 times without pressing the "Accept" button (without saving calibration parameters to the calibration file). With each iteration of the calibration, you will need to keep on the CDP calibration protocol;
3) record the results of each calibration procedure (except the first one) in the tables of common calibration protocol;
4) to process the measurement results.

Measurement error of the FC in the entire range of measurements is calculated by the formula (3.1)

$$\varepsilon_j = t_s \cdot \frac{\sigma_j}{\sqrt{n}},$$

(3.1)

where $t_s(n)$ is the Student’s coefficient for confidence probability $P=0.95$ with the number of observations $n$, $\sigma_j$ – root-mean-square deviation (RMSD).

Calculated error shall not exceed ±0.01.

3.5. The results of the calibration

1. The EMFCM calibration results must be listed in the form of Common Calibration Protocol.
2. The EMFCM, which has been calibrated and meets the requirements of this procedure, is considered to be suitable for use.
In the passport on EMFCM specialist of the metrological service make a mark of the successful passing of the calibration with date and signature and also put a print of the calibration stamp, issued calibration certificates.

3. In case of non-compliance with the requirements of this procedure, EMFCM shall be notified of unsuitability for use.

4. The frequency of calibration – 1 time per 3 months.

### 3.6. Completion of EMFCM calibration

After carrying out EMFCM calibration and registration of results of calibration it is necessary to perform the following operations:

1. turn off the CDP and EMFCM; disconnect CDP from EMFCM;
2. turn off digital indicators of type KSK 18 and disconnect them from load cells;
3. to raise the MW to the transport position;
4. to remove the MW rotation blocker (see Figure 3.2);
5. to remove the STAND from under EMFCM;
6. to remove the EMFCM from the supports.

**Summary:** in this chapter methodology of the test procedure was designed. This methodology consists of different processes and includes:

1) preparation for the calibration,
2) calibration itself,
3) MW radius measurement and calculation,
4) analysis of results, that includes FC measurement error.

The calibration gives as a result additive error value and multiplicative error value; in the aggregate it allows to get valid EMFCM results.
4. SPECIAL ASPECTS OF SAFETY

The development result is a project of a laboratory bench for use in educational and scientific laboratories, presented in the form of a power unit and a control system based on a microprocessor control device. In this case, from the point of view of safety for such developments, the issues of mechanical safety and electrical safety are relevant.

4.1. Electric safety

Electric safety is a system of organizational and technical measures and means to protect people and animals from the harmful and dangerous effects of electric current, electric arc, electromagnetic field and static electricity [23].

Requirements of electric safety are stated in Rules on labor protection at operation of the electric installations [24], Rules of technical operation of electric installations of consumers [25] and other state regulatory requirements of labor protection.

Electrical safety requirements apply to all electricity consumers: employers – legal and physical entities irrespective of their organizational-legal forms and officers as electrotechnical and electrical engineering, Electrotechnology and electrotechnical staff of organizations engaged in technical maintenance of electrical installations, conducting in them of the operational switching, organizing and performing construction, installation, commissioning, repairs, tests and measurements, and also engaged in the management of technological operating modes of objects of electric power industry and power accepting installations of consumers [26].
The stand is designed to work in grounded neutral system, so to reduce the risk of electric shock when working with the stand and to increase the protection of service personnel, it is necessary to make a set of measures to ensure electrical safety of the product operation.

According to [27] p. 1.3 the protective earth or neutral earthing of electrical installations should be performed:

- at rated voltage 380 VAC and above and 440 VDC and above – in all cases;
- at rated voltage from 42 to 380 VAC and from 110 to 440 VDC under the conditions of high risk and especially dangerous in accordance with GOST 12.1.013-78.

The designed stand is designed to work in conditions of high risk, since the frame of the stand is a metal conductive base, therefore it is necessary to calculate the parameters of the protective neutral earthing.

### 4.2. A set of measures to ensure the electrical safety of the product

To ensure electrical safety it is necessary to apply the following measures, and even at the design stage:

a) to turn on the stand, a safe plug with grounding conductor and a control panel with "ON" buttons are used – normally open contact with dependent fixation and "OFF" – normally closed disconnecting contact without fixation. This provides 2 stages of protection when feeding power to the stand;

b) to protect against direct contact with live parts, a transparent non-conductive protective screen must be installed;

c) to apply the protective neutral earthing of the stand.
4.3. Neutral earthing

According to the [27], in electrical installations up to 1 kV with grounded neutral, or grounded output of single-phase current source and grounded middle point of the three-wire DC networks used protective neutral earthing.

Neutral earthing – deliberate electrical connection with a zero protective conductor of non-conductive metal parts that may be energized (see Figure 4.1). In case of emergency short-circuit of one of phases A, B or C to the device enclosure in electrical installations 2 a short-circuit (through the enclosure) occurs between the damaged phase and the zero wire 0. Protection of man from electric shock is providing with the duration of action of the current from the time of closure phase on the enclosure till the time of power failure by means of fuses or automatic switches 1. Tripping device in accordance with the requirements of the IEC60354 is selected so that they are triggered by the increase in short circuit current 3 times the nominal current, if used, fuses and 4.5 times for automatic circuit breakers (in hazardous locations respectively 4 and 6 times).

Figure 4.1 – Diagram of the protective neutral earthing.

Protective grounding or neutral earthing shall provide protection against electric shock in case of contact with non-conductive metal parts that may become energized as a result of damage to the insulation. Neutral earthing should perform
the electrical connection of metal parts of electrical installations with earthed point of the source power supply with protective conductor.

4.4. The calculation of the neutral earthing

1) Calculation of the nominal current consumed by the stand:

\[ I_{\text{NOM}} = 40 \text{A}. \]

2) Selection of the multiplicity coefficient of the current.

Automatic switch with reverse-current characteristic is applied:

\[ k > 3. \]

Let’s assume \( k = 3.5. \)

3) Selection of the rated current of the fuse link:

\[ I_{\text{FNOM}} > I_{\text{NOM}} \]

Let’s assume \( I_{\text{FNOM}} = 50 \text{A}. \)

4) Calculation of the expected short-circuit current:

\[ I_{\text{SCO}} > k \cdot I_{\text{NOM}} = 3.5 \cdot 40 = 140 \text{A}. \]

5) Calculation of the total resistance of the supply transformer:

Based on the power of the transformer, the operating voltage of the secondary side, the method of connection is obtained:

\[ Z = 3,110 \text{ohms}. \]

6) The resistance of the phase wire:

\[ R_{\text{ph}} = 1.2 \frac{\rho_{\text{ph}} l_{\text{ph}}}{S_{\text{ph}}} = 1.2 \frac{0.018 \cdot 3}{2} = 0.0320 \text{ohms}, \]

where \( \rho_{\text{ph}} \) is a phase wire electrical resistivity, \( l_{\text{ph}} \) – length of the wire, \( S_{\text{ph}} \) – wire cross-section.

7) The resistance of the zero wire:

\[ R_{z} = 1.2 \frac{\rho_{z} l_{z}}{S_{z}} = 1.2 \frac{0.018 \cdot 3}{2.5} = 0.0260 \text{ohms}. \]
8) Short-circuit current:

\[ I_{SC} = \frac{U_{ph}}{\frac{Z}{3} + (R_{ph} + R_z)^2} = \frac{220}{\frac{3.11}{3} + (0.032 + 0.026)^2} = 211.8 \text{ A.} \]

\[ I_{SC} > I_{SCO} > I_{NOM} \]

\[ 211.8 > 140 > 40 \]  (4.1)

The condition (4.1) is satisfied; hence the fusible link or the automatic current will trigger and shut off the damaged section.

It is necessary to determine the response time of the machine, which should be less than the time allowed for the corresponding effective touch voltage.

According to the obtained values, the calculated effective touch voltage:

\[ U_{ET} = U_{ph} - I_{SC}R_z = 220 - 211.8 \cdot 0.026 = 214.5 \text{ V} \]

At such a voltage, the contact time should be less than 0.5 s. such requirements are satisfied by the emergency circuit breaker VD1-63 (ECB type AC) 2P 100A 30mA parameters specified in table 5.1:

Table 4.1 – ECB parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal current, A</td>
<td>100</td>
</tr>
<tr>
<td>Rated shut-off differential current, mA</td>
<td>30</td>
</tr>
<tr>
<td>Rated conditional short-circuit differential current, A</td>
<td>3000</td>
</tr>
<tr>
<td>Shut-off time at rated differential current, ms</td>
<td>40</td>
</tr>
</tbody>
</table>

The selected ECB will protect the stand in the event of an emergency.

This chapter discussed such an important aspect of development as the safety of product operation, namely ensuring the electrical safety of the developed stand. For this purpose, a set of measures to ensure electrical safety was proposed.
and the calculation of the tanning system and the choice of the necessary protective shutdown devices were carried out.

4.5. Electromagnetic compatibility

Electromagnetic compatibility (EMC) of technical devices - the ability of technical devices to simultaneously operate under actual operating conditions with the required quality under the influence of unintentional electromagnetic interference and not to create unacceptable electromagnetic interference to other technical means.

In real conditions in the location of electrical equipment operates a large number of different kinds of radio emission, which can be taken into account using the methods of probability theory and mathematical statistics. The operation of the co-operating technical devices is the goal of the EMC as a scientific problem. The subject of the study can be considered as the detection of laws hindering the interaction of working together technical means, on the basis of which recommendations are formed to achieve the goal [28].

Electromagnetic interference, i.e. any electromagnetic phenomenon which may degrade the quality of the plant's operation, is in most cases an integral part of the environment and must therefore be taken into account in the safety analysis. The object of attention is the electromagnetic emission from the source of interference (noise emission), i.e. the attenuation of electromagnetic energy by the source of interference, which can be emitted into the space in the form of electromagnetic fields or spread over the wires by a conductive path [29].

During the work of the developed stand the most probable disturbances are radiated high-frequency noise (electric, magnetic fields and EMF caused by continuous fluctuations and transients). The primary cause of these disturbances is the work of the stepper motor and its driver, namely high-frequency switching
keys. High frequency of key switching is connected with physical principles of stepper motor control and STEP/DIR control.

Microcontroller and microprocessor devices, signal wires and data lines have the greatest sensitivity to this kind of interference.

The following solutions are implemented to ensure functional safety of the stand:

a) applied wires with metal shields. The shield reduces the energy of electromagnetic waves by either absorbing this energy by the conducting environment, or by reflecting the energy in the place of the boundary of the two environment. Magnetic materials protect against electromagnetic energy, and conductors (for example, copper and aluminum) have good reflectivity and protect against electric fields of interference.

b) grounding of the shield from the signal source. If grounding is done by the receiver, the interference current will flow through the capacitance between the cable cores, creating on it and, therefore, between the differential inputs, the interference voltage. Therefore, it is necessary to ground the braid on the part of the signal source. Figure 4.2 illustrates the grounding of the shield. The capacitor is used to attenuate high frequency noise. If the ground is made on both sides of the wire, a closed loop is formed, which will work as an antenna, receiving high-frequency interference. Therefore, grounding should be done only on one side, and on the transmitter side

Figure 4.2 — Shield grounding.
c) applying of open data protocols Modbus RTU, Modbus TCP/IP, allowing in the case of an incorrect frame to filter erroneous (distorted) data, in addition to the comparison of checksums for the interface transmitted and received frames.

4.6. The determination of the safety integrity level

The most important aspect of functional safety is the assignment of the security level to the system.

The safety integrity level (SIL) - discrete level (assuming one of four possible values) corresponding to the range of values of safety integrity, where the safety integrity level equal to 4 is the highest level of safety integrity and safety integrity level equal to 1 corresponds the least to the completeness of the security.

The method 1N presented in [30] will be used to determine the SIL of the system. According to this method, the following procedures must be followed in order to correctly identify the SIL:

1. Determine the subsystem, which consists of the system, related to security.
2. For all elements of each subsystem separately determine the proportion of safe failures (individually for each element having fault tolerance hardware, equal to zero).

The maximum level of security completeness that can be presented to a security-related system is determined by the subsystem with the lowest SIL.

According to [31], the operating conditions of the system correspond to class 3 – electromagnetic environment with parallel laying of power and signal cables.
4.7. Immunity test program

Since the system uses a stepper motor running the STEP/DIR protocol, it is advisable to evaluate the immunity of the system to microsecond pulsed interference of large energy.

As a testing device, microsecond pulse interferences large energy test generator IGM4.2 was applied, the characteristics of which are given in table 4.2.

Table 4.2 – IGM4.2 main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No load amplitude of voltage pulses, kV</td>
<td>(0.5; 1; 2; 4)</td>
</tr>
<tr>
<td>Voltage pulses front duration at levels 0.1-0.9, us</td>
<td>6.5</td>
</tr>
<tr>
<td>Voltage pulse duration at level 0.5, us</td>
<td>700</td>
</tr>
<tr>
<td>Pulse polarity</td>
<td>Positive and negative</td>
</tr>
<tr>
<td>Short circuit amplitude of current pulses, A</td>
<td>(12.5; 25; 50; 100)</td>
</tr>
<tr>
<td>Current pulses front duration at levels 0.1-0.9, us</td>
<td>4</td>
</tr>
<tr>
<td>Current pulse duration at level 0.5, us</td>
<td>300</td>
</tr>
<tr>
<td>Pulse interval, s</td>
<td>&gt;60</td>
</tr>
<tr>
<td>Start mode</td>
<td>single</td>
</tr>
<tr>
<td>Power consumption, W</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Size, mm</td>
<td>450x434x169</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Service life, years</td>
<td>10</td>
</tr>
</tbody>
</table>
Also it is sensible to provide test of stepper driver for immunity against deviations of electrical power supply parameters with the following operational conditions:

- Level of electromagnetic compatibility 2.
- Electrical protection: Class I.
- Nominal voltage 24 VDC.

As a testing device, pulse interference test generator IGA24.1 was applied, the characteristics of which are given in table 4.3.

Table 4.3 – IGA24.1 main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply, V at 50Hz</td>
<td>198-242</td>
</tr>
<tr>
<td>Power consumption, W</td>
<td>&lt;500</td>
</tr>
<tr>
<td>Current protection level, A</td>
<td>1-10.5</td>
</tr>
<tr>
<td>Tested device voltage supply, VDC</td>
<td>27±1</td>
</tr>
<tr>
<td>Size, mm</td>
<td>520x500x330</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>&lt;30</td>
</tr>
</tbody>
</table>

**Summary:** In this chapter such important aspect of development as an electric safety of the developed stand was considered. A set of measures to ensure electric safety was proposed and following tasks were solved:

1. The aspects of ensuring electrical safety are considered, the structures and types of the main and additional protection against electric shock are offered. A class of protection against electric shock is assigned.

2. The aspects of electromagnetic compatibility are considered, the risks and the danger degree of the stand functioning violation are estimated and the measures to ensure noise immunity are proposed.
CONCLUSION

As a result of the master’s paper, the calibration procedure of the friction coefficient measurer was automated, the following tasks were solved:

- a preliminary layout of the calibration platform has been developed,
- developed information management computer system of bench tests,
- the methodical complex of carrying out tests on the basis of the stand in laboratory conditions is developed,
- safety assessment of work with the stand was made, and measures to improve electrical safety were proposed.

The obtained results differ in novelty, since the developed methodical complex of testing, functional scheme, algorithmic and software information control system, implemented on the basis of a personal computer, characterized by an independent ergonomic layout, are applied to a unique stand.

For the future implementation and production it is necessary to research technical aspects of two-dimensional dynamometry and investigate mutual influence of measuring forces on each other and on the final result of the calibration.
REFERENCES


[31] Electromagnetic compatibility of technical equipment [Text]: IEC 61000-4-5-95.
- Instead of GOST R 50007-92; intr. 01.01.2001.