Algorithms and tools for automated diagnostics of a piston compressors

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Abstract. The work is devoted to the creation of the development of algorithms for the effective diagnosis of compressors used in urban electric transport in order to timely detect malfunctions and breakdowns. A stand is considered for studying the working processes of compressors and checking the effectiveness of design measures aimed at improving performance, as well as assessing the effect of various types of air bleeding from the flow path on its gas-dynamic parameters. The main characteristics and parameters are considered.

1. Introduction
Diagnostics today is a fundamental element in improving equipment repair, as it helps to identify breakdowns and reduce the time between repairs. The use of all kinds of modern diagnostic tools and methods will make it possible to check the state of the parameters in a timely manner, which will make it possible to reduce the number of failures, as well as speed up repairs or ultimately avoid it. For a complete assessment of the operating condition, an integrated approach and a competent assessment of reliability are required, with further prediction of its performance [1, 13].

As a result of the analysis, the authors considered the development of a special stand for testing the trolleybus compressor (Figure 1), thanks to which the repair and diagnostics system will be improved. Compressors are machines that compress atmospheric air to the required pressure. Due to the fact that the need for compressed air on a trolleybus is small, they are mainly equipped with piston compressors. Air is compressed in reciprocating compressors by a reciprocating piston inside the cylinder. It is known that the state of a gas is determined by the specific volume (volume of 1 kg or 1 kg of gas), pressure in N/m² (kg/cm²) and temperature [2-4]. The processes of changing the state of the gas in the compressor cylinder occur in the following order [11, 12]:

1) intake of atmospheric air into the cylinder cavity (when the piston moves from top to bottom dead center);
2) compression of atmospheric air in the cylinder cavity (when the piston moves to top dead center);
3) release of compressed air from the cylinder cavity into the reservoirs (when the piston moves in the top dead center zone).
Figure 1. Scheme of operation of a reciprocating compressor: 1 - Inlet valve; 2 - Inlet receiver; 3 - Upper suction valve; 4 - Lower suction valve; 5 - Upper discharge valve; 6 - Lower discharge valve; 7 - Cylinder; 8 - Plunger (piston); 9 - Emergency valve; 10 - Outlet receiver; 11 - Outlet valve; 12 - Stem; 13 - Crosshead (crosshead); 14 - Crosshead pin; 15 - Connecting rod; 16 - Crosshead oil supply channel; 17 - Main bearings; 18 - Bed; 19 - Crankshaft; 20 - Oil; 21 - Coupling; 22 - Blowing motor; 23 - Main engine blowing; 24 - Main engine; 25 - Oil channel valve; 26 - Water channel valve.

2. Main characteristics

A Pressure. This characteristic can generally be called fundamental, since it reflects the main function of the compressor - to compress the gas, which leads to an increase in its pressure. Compressor pressures are usually measured in Pascals (Pa), bar (bar), or atmospheres (atm), but millimeters of mercury (mmHg), kilogram-force per square centimeter (kgf/cm²), or pounds per square inch (PSI). The most common units of measurement are Pa and bar, which correlate as follows: 1 bar = 0.1 MPa. Also, the working pressure is subdivided into excess (Psub) and absolute (Pabs). Their values differ by the value of atmospheric pressure (Patm) and are related by the relation 

\[ P_{izb} = P_{abs} - P_{atm}. \]

Depending on the developed pressure, the compressors are divided into:

- vacuum (vacuum more than 0.05 MPa);
- low pressure (from 0.15 to 1.2 MPa);
- medium pressure (from 1.2 to 10 MPa);
- high pressure (from 10 to 100 MPa);
- ultra-high pressure (over 100 MPa).

A Performance. Compressor capacity refers to the amount of gas discharged per unit of time. It is usually measured in m³/min, l/min, m³/h, etc. The value of the compressor capacity can be indicated for the suction side and the pressure side, which are not equal to each other, since the gas changes its volume during the compression process. For the case of inlet capacity, standard conditions are usually taken, that is, at atmospheric pressure and a temperature of 20°C. The choice of how to indicate the compressor capacity may depend on the ease of perception depending on the application of the device. The recalculation of the gas flow rate from the conditions at the inlet to the output conditions can be carried
out using special formulas. Also, recalculation of performance may be required if the gas has a different temperature.

Depending on the capacity, the compressors are usually divided into devices:

- high productivity (more than 100 m³ / min);
- average productivity (from 10 to 100 m³ / min);
- low productivity (up to 10 m³ / min).

In the general case, power, following the standard definition, is the amount of work performed over a period of time to the duration of this period. In the case of a compressor, it is the product of the gas capacity by the compression work.

Theoretical power:

\[
N_t = \frac{(Q \cdot \rho \cdot A)}{1000},
\]

Where

- \(N_t\) – theoretical power, kW;
- \(Q\) – productivity, m³/min; \(\rho\) – gas density, kg/m³;
- \(A\) – theoretical work of gas compression, J/kg.

Compressor unit capacity equipped with engine and gear:

\[
N_d = \frac{N}{(\eta' \cdot \eta_{tran})}
\]

Where

- \(N_d\) – engine power of the compressor unit, kW;
- \(\eta'\) – engine efficiency;
- \(\eta_{tran}\) – mechanical transmission efficiency.

Total air flow in the pneumatic system:

\[
G_c = G_T + G_D + G_P
\]

To convert the amount of consumed air into a volumetric measurement (with a specific gravity of air = 1.3 kg/m³), use the equation:

\[
V_k = 1000 \frac{G_T}{1.3} \text{ l/min.}
\]

3. Purpose and composition of equipment

To manufacture the necessary equipment, you need to determine what characteristics the compressor should have. To determine the characteristics, they are guided by the average value of the demand for compressed air. To calculate it, it is necessary, based on the operating experience and knowledge of the technology of the planned work, to imagine what the duration and frequency between the compressor starts, is it possible for several devices to operate simultaneously. You need to know the technical characteristics of the reciprocating compressor used, including the volume of the receiver, as well as formulate specific complaints about its operation. In our compressor, air is compressed in the closed space of the cylinder as a result of the reciprocating movement of the piston. Structurally operating model of the compressor is a unit that includes an electric drive, a receiver and a device for pressure control (pneumatic reducer). The argument in favor of making a working model of a test bench is determined by their acceptable weight and dimensions, ease of operation and maintenance, and output characteristics that can satisfy the needs of almost any person.

The stand is designed to perform the following tasks:

1) research of working processes in the flow path of model and full-scale compressors and checking the effectiveness of design measures aimed at improving performance;

2) determination of gas-dynamic characteristics of the tested compressor at variable operating modes;
3) assessing the influence of various types of air bleeding from the compressor flow path on its gas-dynamic parameters.

Therefore, an automated experimental stand for testing GTE compressors is a production room with a set of power, power transmission and energy-consuming equipment installed in it with auxiliary and service mechanisms that make up a bench power plant (St.EU). As well as a set of measuring equipment that allows you to control the operation of all bench units, conduct experimental research in a given mode with the recording of the necessary parameters of the test object.

The bench installation includes:
- closed test box;
- observation cabin;
- technical and auxiliary premises;
- premises for placing a complex of secondary measuring equipment and computers;
- main bench equipment and systems for testing;
- measuring and computing system (ICS) for automated collection and processing of data during testing;
- auxiliary equipment.

The main bench equipment includes the following units:
- drive gas turbine engines (GTE);
- device for increasing the rotational speed transmitted from the drive motors (multipliers);
- device for determining the power transmitted to the tested compressor from the drive motors;
- object of research (tested compressor);
- foundation and intermediate mounting frames;
- device for equalizing the pressure field at the inlet to the testing compressor (receiver);
- a system of air and gas venting devices (snails, a system of throttles and adjustable dampers, gas ducts, air intake shafts).

4. Automated diagnostics control system and work algorithm

When operating the stand, it is necessary to have data on the values that characterize the processes occurring in different parts of the unit under study. During operation, these data are used to monitor the operation, the state of structures, to automatically control parameters and to perform other functions related to the automation of processes. These functions - control, regulation and others, are very often performed using electrical quantities proportional to the required parameters, since electrical quantities are most convenient for building visual and recording instruments, measuring elements of regulators, for transmission over a distance. In this case, the measurement of non-electrical quantities is carried out by means of electrical converters controlled by the system. The authors proposed a measuring and computing complex, the structural diagram of which is shown in Figure 2.

The system is designed:
1) for automatic collection and processing of test data of full-scale and model compressors at experimental stands;
2) automated processing of data entered into the system from information carriers and a computer console;
3) performing scientific and technical calculations.
The software allows you to check the technical condition of the stand, diagnose its malfunction, and determine the metrological characteristics.

At the command from the operator's panel, the USO (device for communication with the object) receives a request to execute the program for calling the parameters for printing or for digital indication. The USO, having formed a launch command, transmits it through the intra-system communication modules (IVS) to the UVK SM-2M. Upon the received command, the CM-2M UVK collects information about the state of the parameters of the tested object.

In this case, information from the sensors in analog form comes from the measuring complex to the USO, where normalization, switching, coding of the signal of each parameter and its sequential
transmission in digital form through the MVS and the communication line to the UVK CM-2M take place.

The information from the sensors received by UVK SM-2M is subjected to mathematical processing, and a test report of the object is formed in the appropriate form (Figure 3).

The processed information is transmitted to the observation booth through the chain UVK SM-2M - fast data transfer module (MBPD) and then to indicate the parameters to the display module or to print the parameter protocol to a sign-synthesizing printing device (UPZ).

Information about the state of the controlling parameters is entered through measuring transducers with a unified output of 0-5 mA.

The current outputs of the measuring transducers are connected to the inputs of the normalization modules (MH), which are used to proportionally convert the current signals of the transducers into voltage signals of 0-5 V, as well as to filter signals from general industrial noise.

To convert the voltage signals of the converters into a digital binary code, an analog-to-digital converter (ADC) is installed in the USO, to the input of which signals from the converters are alternately connected using a contactless switch (KB), programmed from the SM-2M. Further, the signals in digital form are fed to the CM-2M UVK for mathematical processing. To measure the parameters, the device and the compressor are equipped with appropriate sensors in the control sections.

![Figure 3. Placement of sensors on a reciprocating compressor.](image)

The most widespread are electromagnetic sensors, since they have a number of advantages over other types of sensors: simplicity of the device, high reliability, the ability to connect to industrial frequency sources, and relatively high output power. In these sensors, the output electrical quantity is determined by the change in the position of the moving parts of the device. Commercially available electromagnetic linear and angular displacement sensors, possessing good sensitivity, reliability and stability of parameters under conditions of high mechanical and climatic loads, are widely used in various devices.
A specialized measuring and computing system is a territorial, isolated two-level computing complex based on a typical control computing complex and a terminal station (TS) (Figure 4), which includes a communication device with an object based on communication subcomplexes, as well as special devices for measuring the speed, torque, liquid levels, liquid consumption, etc.

Each list object has properties. Properties - any characteristics of an object. Properties can be both the model of the unit and the level of its vibrations, for example. The properties can be changed while editing the object in the configurator, during the execution of rules, or they can be assigned values corresponding to the readings of the sensor installed on the unit.

5. Design and mathematical description

The main area of the test bench is occupied by a closed box, in which all the main units of the bench are installed. Assembled according to the scheme "drive motors - multipliers - device for determining the transmitted power (PCM) - tested compressor" they constitute the stand transmission (Figure 3). Drive motors 1 are mounted on intermediate frames 6, which, in turn, are placed on a common foundation frame together with gas ducts 9. For the convenience of removing the gas ducts outside the test box, one of the engines must be displaced and an intermediate support installed for it 12. Multipliers 2 and 3 are placed on a separate frame 7. The tested compressor 5, its volute 10 and PCM 4 are installed on a single foundation frame 8. A receiver 11 is located in front of the tested compressor, fixed to the foundation. The receiver and the tested compressor are connected by an adapter 13, through which the air is taken in by the compressor 5.

Depending on the purpose and task of testing the compressor, the preparation of the flow path can be completely different, up to the installation of pressure and temperature sensors behind each stage.
Distinguish between primary and secondary processing of test results. The primary processing of the results obtained consists in averaging the flow parameters in the control sections and converting the measured values into SI units. 

The values of the measured parameter A obtained for each receiver of the comb are averaged over the expression

\[ A = \frac{\sum_{i=1}^{n} A_i}{n}, \]

Where n - is the number of measurements at each regime point. 

After that, averaging is performed between the individual receivers of the comb. The obtained average value of the parameter in the control section is used in further calculations. Conversion of measured values of parameters into true values is performed according to calibration charts or analytical dependencies. 

Secondary processing of test results is carried out in the following sequence. 
1. The degree of pressure increase in the compressor is determined as the ratio of the absolute total pressures in the sections

\[ p^*_k = \frac{p^*_2}{p^*_1} = \frac{B + \Delta p^*_2}{B - \Delta p^*_1}, \]

Where B - atmospheric pressure, kPa; 
\( \Delta p^*_1(2) \) – excess total pressure upstream and downstream of the compressor, respectively.

2. Reduced speed in the flow meter

\[ \lambda_1 = \sqrt{k + 1 \left[ \frac{k - 1}{k - 1 - \left( \frac{p_1}{p^*_1} \right)^{k - 1}} \right]}, \]

Where:
\( p_1 = B - \Delta p^*_1 \) – absolute static pressure in the flow meter, kPa;
\( p^*_1 = B - \Delta p^*_1 \) – absolute total pressure in the flow meter, kPa.

3. Mass airflow through the compressor is determined taking into account the calibration factor

\[ G = k_G m q \left( \frac{p^*_1}{\sqrt{T^*_0}} \right) \cdot 10^3, \text{ kg/cm,} \]

Where \( k_G \) is the calibration coefficient of the flow meter;
\( m \) - is the parameter of the type of gas;

\[ m = \sqrt[\frac{k}{R} \left( \frac{2}{k + 1} \right)^{k - 1}}; \]

for air \( m = 0.0403 \text{ (kg K / J)}^{0.5} \);
$T_0^*$ – total temperature at the compressor inlet, K;

$q(\lambda)$ – gas-dynamic flow function, which can also be determined by tables of gas-dynamic functions or by the formula

$$q_i(\lambda_i) = \lambda_i \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \left[1 - \frac{k-1}{k+1} \lambda_i^k\right]^{\frac{1}{k-1}}.$$  

4. Compressor speed

$$n = \frac{60f}{i},$$

Where $f$ - is the number of impulses recorded by the chronometer-frequency meter in one second;

$i$ - is the number of protrusions on the rotating shaft.

5. Torque on the compressor shaft

$$M = k_M f (\varphi_{\text{max}} - \varphi_0) \cdot N \cdot m,$$

Where $k_M$ is the coefficient of static calibration of the torsion spring;

$f$ – readings of the frequency counter-chronometer;

$\varphi_{\text{max}}$ – maximum spring twist angle, degrees;

$\varphi_0$ – initial twist angle, determined from the results of dynamic calibration of the torsion spring, deg.

6. Power consumed by the compressor

$$N_k = \frac{M \cdot n}{60} \cdot 10^{-3}, \text{ kw.}$$

6. Conclusions

Thus, according to algorithms and design solutions, we get a ready-made stand, synthesized according to calculations. Designed for modern and fast compressor diagnostics. The stand is highly efficient, and its operation greatly speeds up and simplifies diagnostics. With the help of the IVS, an automated collection of information on the functioning of the main units and systems of the test bench is also carried out. The information collected in this way from the primary sensors through the complex of secondary converting equipment enters the computer, where it is processed in accordance with the software.

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