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Improving the maintenance program for passenger elevators based on simulation of their operating modes

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Introduction. Elevators in residential and public buildings are the means of vertical transport. An elevator is one of the complex electromechanical devices of increased danger. Therefore, all stages of its life cycle are strictly limited by regulatory documents. The desired levels of safety and comfort are provided through the reasonable choice of the basic parameters and a constant maintenance of the system in good condition. The key factors that affect the implementation of regulatory requirements during the operation of the elevator installation are the quality of manufacturing of critical components, the level of real workload, taking into account the actual value of the spent resource, and the implemented maintenance program. Currently, when determining the maintenance schedule for elevators, such characteristics as the density of occupancy, the level of power loads, the actual operating time of the elevator and the counts of starts of the main drive are not taken into account. This study objective is the scientific rationale of the concept and methodology for developing the program of maintenance of specific elevator installations on the basis of studies of the level and mode of loading of load-bearing units.

Materials and Methods. The use of simulation modeling techniques to assess the load level of power units of an elevator installation and its kinematic indicators under the action of numerous random impacts is validated in the paper. The development of an indicator that characterizes the complex mode of elevator operation, taking into account the joint influence of the level of resource development, net operating time, number of starts, and the power load of the nodes, required the application of an expert method. The final part of the research program is the formation of specific recommendations on the maintenance schedule of elevators. It is based on the ranking of particular indicators.

Results. The performance feature of the elevator installation is that the service time of a customer is a function of many random variables. Mathematical models of the formation of force impacts are based on the representation of an electromechanical elevator as a dynamic one-degree-of-freedom system. Expressions for calculating the static tension of traction ropes and torques on the motor shaft are obtained. The problem of dynamics is solved. The loads whose values are the basis for performing simulation modeling of the operating modes of the elevator installation are determined.

Discussion and Conclusions. Feasibility of the regulations for the maintenance of passenger elevators is an urgent task, the solution to which determines the level of safety and comfort of passengers. Currently, the standards for the design and operation of elevator installations do not link the frequency of maintenance programs with the level of load and the amount of resource development. The paper provides a general statement of the problem and a methodology for the formation of a complex factor of the equivalent load. Mathematical models are given for calculating the power and temporary loads of the elevator, taking into account the nature of numerous random impacts.

Keywords: passenger elevator, random impacts, mathematical models of functioning, dynamic loads, power loading mode, distribution of random factors, kinematic indicators, simulation, complex load factor, maintenance program.

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Introduction. According to the main regulatory document[1], an elevator is a device designed to move people and (or) cargo from one level to another in a cabin moving along rigid guides, whose angle of inclination to the vertical is no more than 15°. The elevator is a unique public transport vehicle. It is operated by the passenger or by personnel who do not require high qualifications [1]. Therefore, the elevator must meet all the requirements of safety and comfort when transporting passengers. The elevator is one of the complex electromechanical devices of increased danger [2]. The design, manufacture, installation and maintenance of elevators during operation are subject to strict requirements formulated in the Technical Regulations and other regulatory documents. Depending on the type of drive, there are electromechanical and hydraulic elevators [3]. In electromechanical elevators, a drive consisting of an electric motor, a gearbox and a traction sheave, is used as a lifting mechanism (Fig. 1), and in hydraulic elevators — a linear hydraulic drive.

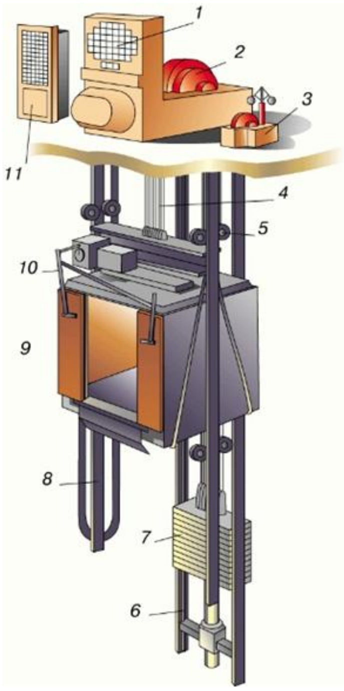

Fig. 1. Elevator design with electromechanical drive: 1 — electric motor; 2 — winch; 3 — speed limiter; 4 — traction ropes; 5 — guide rollers of the cabin; 6 — counterweight guides; 7 — counterweight; 8 — cab guides; 9 — cabin; 10 — door mechanism; 11 — control panel

The most widespread in modern multistorey buildings are electromechanical driven elevators [4]. In this paper, the subject of research is an elevator with geared electromechanical drive.

According to the information of the National Elevator Union, at the end of 2020, there were more than 500 thousand elevators in the Russian Federation operated in the housing stock and various institutions[2]. About 160 thousand of them have worked out the established standard period, but continue to operate. The number of new multistorey buildings across the country is increasing every year, which causes an increase in the fund of elevator equipment.

[1]Technical regulations of the Customs Union. Elevator safety. Decision of the Customs Union Commission No. 824 of 18.10.2011 (ed. of 19.12.2019) “On the adoption of the Technical Regulations of the Customs Union “Elevator Safety”. URL: https://docs.cntd.ru/document/902307835/ (accessed: 11.06.2021). (In Russ.)

[2] Data of the National Elevator Union of the Russian Federation. URL: http://www.lift.ru/index.php/ru/ebiblio.html/ (accessed: 11.05.2021). (In Russ.)

The most important requirements for elevator equipment are the safety and comfort of passengers, which can be ensured due to the correct selection of parameters of the vertical transport installation and the constant maintenance of the elevator in good condition [4–5].

The following groups of factors have the main influence on the elevator safety indicator:

— quality of manufacturing of elevator equipment;

— load level of the load-bearing elements and its used resource amount;

— ongoing maintenance program.

Safety of the elevator[3] is characterized by generally accepted indicators: MTBF, probability of failure-free operation, availability factor.

The indicator "transport comfort" is introduced by the national standard[4]. It characterizes the lift interval, expressed as the time period between two consecutive departures of the elevator cab in a given direction on the main landing floor, where people entering the building have access to the elevators. Thus, the level of comfort is the conditional waiting time the passenger waits for the next flight. Note that the indicator of transport comfort is a random variable, and, naturally, in real conditions, it changes from the minimum to the maximum value. The most representative value of the comfort indicator may be the average value in different periods of daily operation.

Let us turn to the elevator maintenance programs. The elevator equipment servicing is established based on two main documents: the equipment technical passport and the "Rules..."[5]. The frequency is assumed to be the same for all elevator facilities.

In recent years, a number of fundamental studies have been carried out in Russia [4–6][678] and abroad [7–10], related to the reliability and safety of elevator equipment. It should be noted that in the considered works, when determining the maintenance intervals of elevators, such parameters as the density of the population of floors and apartments, as well as the level of power loads, the actual operating time of the elevator, the number of starts of the main drive per unit of time, are not taken into account.

Despite the same number of floors, the same type and number of elevators, similar buildings can significantly differ in the number of residents, as well as in the degree of operation of elevator equipment. This has a significant impact on the net operating time, the equivalent loads experienced by the elevator equipment, which changes the real rate of resource development, the service life of each set of elevator equipment. At the same time, their planned assigned lifespan will be the same.

It is important to note that currently, the normative[3,4,5] and literary domestic [6][6,7,8] and foreign [7–10] sources lack a definition and recommendations for the application of criteria for the loading of elevators. There are also no analytical and engineering methods for designing elevator maintenance programs in the development of research, design and operating organizations. Lack of a methodological base for the design of the elevator maintenance system and program leads in some cases to an excess of the required amount of repair impacts with a simultaneous increase in costs, in others — to an unjustified increase in the repair interval. This affects the reduction of reliability indicators and, in general, safety during the operation of elevator installations.

To maintain the level of safety and comfort of elevator installations with the required and sufficient level of repair impacts, this study provides for research in the following areas:

— use of simulation modeling to establish real equivalent loads and operating modes;

[3] National standard of the Russian Federation. Lifts. General safety requirements in service: GOST R 55964-2014. Federal Agency for Technical Regulation and Metrology. Moscow: Standartinform; 2019. 16 p. (In Russ.)

[4] National standard of the Russian Federation. Passenger lifts. Planning and selection for residential buildings: GOST R 52941-2008. Federal Agency for Technical Regulation and Metrology. Moscow: Standartinform; 2008. 15 p. (In Russ.)

[5] Regulations for safe use and maintenance of elevators, lifting platforms for the disabled, passenger conveyors (moving pedestrian paths) and escalators, with the exception of escalators in subways. Decree of the Government of the Russian Federation No. 743 of June 24, 2017. URL: https://docs.cntd.ru/document/436745439#/reg/ (accessed: 11.06.2021). (In Russ.)

[6] Mechiev AV. Development of ways to ensure safe operation of elevators: Cand.Sci. (Eng.), diss., author's abstract. Moscow, 2018. 18 p. (In Russ.)

[7] Gorozheev MYu. Development and research of a device for express diagnostics of elevators during operation: Cand.Sci. (Eng.), diss., author's abstract. Moscow, 2013. 25 p. (In Russ.)

[8] Fedyaev RV. Methods of improving the reliability of elevators and lifts: Cand.Sci. (Eng.), diss., author's abstract. Tomsk, 2013. 23 p. (In Russ.)

— justification of a complex indicator, which helps to form an assessment of the load level of the power elements of the elevator;

— development of recommendations on the maintenance intervals of elevators in both already operated and designed buildings.

This will provide for the control of the correctness of the design decisions made (primarily, according to the parameters of the main drive), and, due to the effective organization of maintenance, the reduction in the likelihood of equipment failures.

It should be noted that when modeling elevator installations in operation, it is possible to use kinematic parameters of the mode obtained as a result of observations of dispatch services: net machine time and specific number of starts [11]. For these elevators, it is crucial to obtain data on power loads as a result of modeling.

Under a complex modeling of the operating modes of the designed elevators, it is required to solve the problem of selecting their key parameters beforehand.

The research objective is to scientifically substantiate the concept and methodology for developing a maintenance program for specific elevator installations based on studies of the level and loading mode of the main load-bearing units during a given or predicted period of operation.

Materials and Methods. Continual problem setting. In accordance with the general concept of the problem solving and to achieve the objective of this study, the structure of tasks and methodological support for each direction are determined. First of all, it is planned to describe the modeling object as a queuing system operating in a cyclic mode and subjected to random external actions. It is required to study a set of random factors affecting the main drive of the elevator installation beforehand.

Simulation modeling is recognized as an effective methodological technique for studying the patterns of work processes under the conditions of random actions. To implement the modeling procedures, it is required to validate mathematical models of the formation of force effects on the elevator installation drive, and models of the formation of random action distributions. The main influencing random factors include the number of passengers in the cabin of a random flight, the numbers of the floors of standing, calling and destination, the number of stops during the cycle, the duration of net machine time, and the total cycle duration.

It is planned to develop algorithms and programs for simulating the impact of the key factors on the equivalent load value and kinematic characteristics of the operating mode of the elevator drive on the basis of one of the modern programming languages.

It is required to assess the adequacy and analyze the results of simulation and power modeling to build generalized dependences of the impact of the key factors on the operating parameters of elevator installations.

For the first time, it is planned to form conceptual approaches to the development of maintenance programs for elevator equipment in connection with the real modes of its loading and the subsequent development of an engineering methodology for the formation of the maintenance regulations for an elevator installation.

The paper gives the results of presenting an elevator as a queuing system, the selection of the equivalent load indicator, the model of the formation of force effects on the main drive shaft. Other stages and results of modeling of kinematic indicators and power modes will be described in the next issues of the journal.

Research Results. Elevator as a queuing system. For an adequate mathematical description of the functioning of a passenger elevator in a multistorey building, it is required to accept some obvious conditions that determine its basic properties. Each elevator installation is characterized by passport parameters that determine the working conditions and its capabilities:

— number of floors of the house, N;

— maximum load capacity, expressed by the weight of the lifted cargo Q, kg, or the number of passengers, R;

— steady-state speed of the cab (and counterweight), v, m/s.

First, it should be accepted that the operation of the elevator installation when moving passengers is carried out in separate cycles. Each i-th cycle consists of separate stages: the appearance of users, their random number r, on a random floor M and the call of the elevator; at the end of the previous cycle, the elevator cab is on a random floor L; the cab moves at Q=0 during the call period from floor L to floor M; boarding r passengers on floor M and moving to a random destination floor S, 1≤r≤R; during movement on the section M→S, there may be intermediate stops random by number Y and location in the building for pick-up and drop-off of individual passengers; passenger drop-off on the destination floor S; at the end of the cab movement in the i-th cycle, there is a pause of random duration Δ_i — waiting for the next cycle.

It follows from the description that the elevator can be presented as an original single-or multi-channel queuing system (QS) [12], operating in the mode of exposure to a number of random factors — M, L, S, r, Y, Δ. A distinctive feature of the elevator QS is that the duration of the request service from the moment of the call to the passenger's delivery to the final floor of the destination S is a function of many random variables. Each of the random variables (M, L, S, r) are independent. The distribution functions of these quantities can be established either experimentally or on the basis of logical analysis. A separate problem is solved to establish a random variable — number of intermediate stops Y [13,14]. The well-known classical solution can only be used to describe the random waiting time for the next cycle Δ.

In QS theory, it is proved that, if

a) probability of arrival of another application $p_n(t)$ depends only on the time interval between applications t,

b) two events never happen at the same time,

c) probability that at least one event will occur in a very small-time interval Δt, selected at any moment, then probability $p_n(t)$ is expressed by the Poisson law [12]:

$$p_n(t) = \frac{(\lambda t)^n e^{-\lambda t}}{n!}.$$

The distribution of the time interval between two consecutive random events T obeys an exponential law, i.e.

$$P(T>\tau)=e^{-\lambda\tau},$$

where the average value of the random variable T is

$$\tau_{cp}=1/\lambda.$$

Thus, to simulate a flow of applications received at the entrance of a single elevator, we can adopt an exponential distribution law of interval Δ. At the same time, it is required to establish the average waiting time for the next Δ_{cp} application on the basis of experimental observations or regulatory data. The solution to this problem, as well as the justification of the distribution functions of random variables *M, L, S, r, Y* are given in papers [13, 15].

The selection of the indicator of the equivalent load of the elevator is an independent task. First, it is required to determine the criterion that this indicator should meet. This criterion should be interconnected with the conditions for assigning or changing the frequency of maintenance of the main units of the elevator installation. The basic condition is the accumulated consumption of the unit resource in comparison to its normative value. It is obvious that the resource consumption of a unit or part is determined by two factors: time and power, i.e., the equivalent load indicator should take into account the load distribution during operation so that with an increase in the duration of operation and the magnitude of the perceived loads, the equivalent indicator increases. It is proposed, by analogy with the assessment of the load of an electric motor during long-term operation with a high frequency of starts, to take the standard load for the entire inter-repair period of operation of the elevator[9] as an indicator of the equivalent load $M_{экв.}$ with its correction through introducing the relative frequency of starts into the calculation.

Taking into account the above arguments, the proposed mathematical model for calculating the equivalent load of the power elements of the elevator will have the form:

$$M_{ЭКВ} = K(V_{RT}) \cdot \sum_{i=1}^{C} \left(\sqrt{\frac{\int_0^{t_{Bi}} M_{Bi}^2(t)dt + \int_0^{t_{ПД.i}} M_{ПД.i}^2(t)dt}{\tau_i}} \right),$$

where $M_{Bi}(t)$, $M_{ПД.i}(t)$ — accordingly, the moments on the engine shaft (or in another link of the elevator transmission) in the function of time t in the total periods of the elevator call t_{Bi}, of the movement $t_{ПД.i}$ of the elevator cab with passengers;

[9] Epifanov AP. Fundamentals of electric drive. St. Petersburg: Lan'; 2009. 192 p. (In Russ.).

τ_i — the duration of the full i-th cycle of the installation, including the duration of the cab movement when calling, with passengers, braking, pauses for pick-up and drop-off of passengers, as well as waiting for the next application to use the elevator, s;

C — the total number of cycles for a given period of time T;

V_{RT} — frequency of the elevator activation cycles for the calculation period T, i.e., the number of cycles per unit of time, 1/hour or 1/day:

$$V_{RT} = \frac{C_1}{T} = \frac{C_1}{\sum_{i=1}^{C} \tau_i};$$

$K(V_{RT})$ — correction factor that takes into account the frequency of switching on the elevator; coefficient variation limits $K(V_{RT})_{мин} \leq K(V_{RT}) \leq 1$ are established by experts.

At drive switching frequencies close to the standard ones, $K(\nu_{RT}) = 1$ With an increase in the switching frequency V_{RT} , the equivalent load increases due to an increase in coefficient $K(V_{RT})$;

C_1 — the number of starts of the main drive for the estimated time T, i.e., during the periods of calling the elevator, movement with passengers and intermediate stops.

It is appropriate to identify repetitive bulk modes, which will mainly determine the equivalent load over the observation period. At this stage of research, it is proposed to divide the daily period of elevator operation on working days into four-time segments [10].

Rationale for mathematical models of the formation of force actions on the elevator installation drive. Load *M* during the execution of the elevator operation cycle at a certain time interval τ_i can be presented by random graphs *M(t)* for the stages of calling and moving with passengers (Fig. 2).

As previously shown, during the same time interval between maintenance, the elevator can perform a different number of operating cycles, which, in turn, will have different characteristics in terms of duration τ_i and the magnitude of loads $M_{экв}$, taken by the engine and other elements of the elevator.

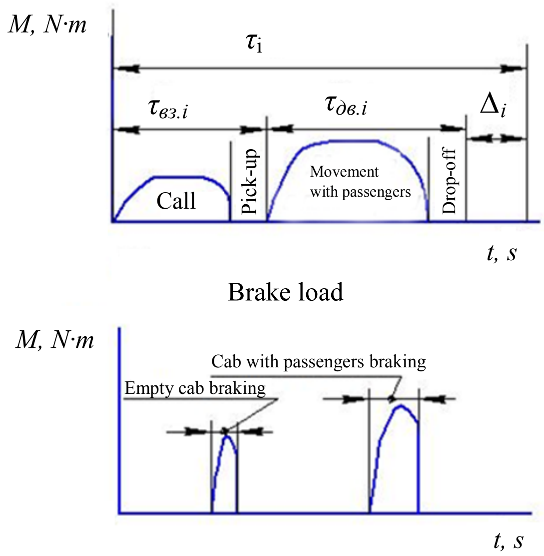

Fig. 2. Elevator operation cycle: τi — cycle time; τвз.i — call time; τдв.i — time of movement with passengers; Δi — time after which the application for the use of the elevator is received

after the end of the cycle The duration of the application execution, the amount of load on the drive and power equipment of the elevator will be affected by random variables: M_i=1, 2 …N; L_i=1, 2,…N; S_i=1, 2,…, N, where N — the number of floors of the house; the relative level of loading of the elevator by load capacity; $\gamma=Q_i/Q_{пасп}$, $\gamma_{мин}<\gamma<\gamma_{макс}$, where $Q_{пасп}$ — the nominal (passport) load capacity; the waiting time interval Δ_i.

To find the dependence of the loads on the power units of the elevator on time when exposed to the listed random variables, we will focus on determining the loads that the power parts of the elevator equipment undergo.

Traction ropes (force S_{k1}) and counterweight ropes (force $S_{п1}$) at any time undergo static loads at the points of run-on and run-off from the traction sheave (TSh), which correspond to the design scheme and are determined from the formulas (Fig. 3):

— when lifting and lowering the cab

$$S_{k1} = \frac{(Q_i+Q_k)\cdot g \pm (F_k+F_г)}{\eta_б^2} + n \cdot q_{тк} \cdot (H - \Delta h) \cdot g; \quad (1)$$

— when lifting and lowering the counterweight

$$S_{п1} = [Q_п \cdot g \pm F_п] \cdot \eta_б + n \cdot q_{тк} \cdot \Delta h_i \cdot g. \quad (2)$$

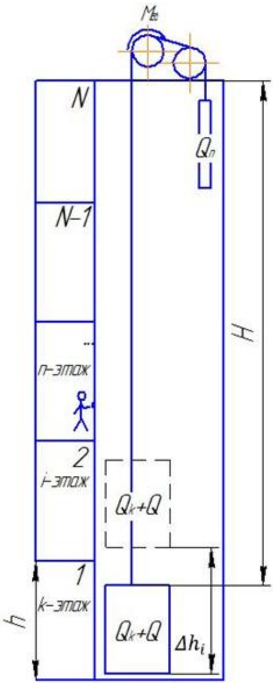

Fig. 3. Scheme for the calculation of forces in traction ropes

The sign "plus" — when the cab or counterweight moves up, "minus" — when the cab or counterweight moves down. The formulas indicate: Q_i — weight of the cargo in the i-th cycle, kg; Q_K — weight of the cab, kg; $Q_П$ — counterweight, kg; F_K — resistance force to the cab movement, N; $F_Г$ — resistance force to the movement of the cargo, N; $F_П$ — counterweight movement resistance, N; $\eta_б$ — efficiency of the rope system unit; n — the number of traction ropes; $q_{тк}$ — bulk mass of the traction rope, kg/m; Δh_i — the distance between the levels of the first floor and the location of the cab with passengers at a given time (Fig. 3).

As can be seen from formulas (1) and (2), the tension of the branches of the traction ropes and the counterweight ropes at the points of run-in and run-off from the TSh depends directly on the following factors:

— the direction of cab movement and, accordingly, 0 counterweight;

— distance Δh_i, which determines the random location and movement of the cab. In turn, the change of Δh_i occurs depending on the random combination of floor numbers M_i, L_i, S_i in this cycle;

— random value of the mass of the transported passengers Q_i.

In addition to static loads acting on the elevator ropes and transmitted to its drive elements during periods of stationary state and steady motion (TSh, gearbox, engine, braking device), the system also undergoes dynamic loads during periods of unsteady movements during starts, braking, etc.

A typical circuit of the elevator drive and transmission is shown in Fig. 4. In this case, the scheme of the gear drive is considered. Nowadays, gearless drive systems with a motor that has a frequency control to change the speed are spreading. These systems require a separate study that goes beyond the scope of this work.

We will consider the set of kinematically connected elements "engine — gearbox — TSh — ropes — cab — counterweight" as a one-degree-of-freedom system. Under real conditions, the cab and the counterweight suspended on the ropes can perform, in addition to general kinematically coordinated movements together with all the elements, additional oscillatory movements and cause corresponding loads in the ropes and other elements connected to them.

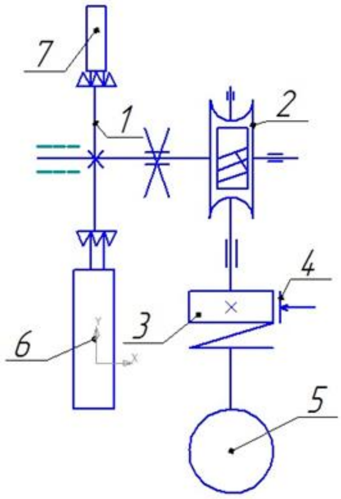

Fig. 4. Calculation kinematic diagram of an elevator with a gear transmission:
1 — TSh; 2 — worm gear; 3 — coupling with a brake pulley; 4 — shoe brake;
5 — electric motor; 6 — cab; 7 — counterweight

To solve such a problem, it is required to present the elevator drive system in at least a three-mass formulation. It should be noted that low-frequency vibrations of the cab during the movement of passengers significantly worsen the level of comfort, therefore, design solutions are provided that exclude the occurrence of oscillatory processes.

In the future, we will consider a set of interrelated parts as a reduced one-mass system[10]. The reduction center is the axis of rotation of the electric motor. As can be seen in the diagram shown in Fig. 4, the loads from the gravity forces of the cab and the counterweight are not applied directly to the electric motor, but are transmitted through a number of intermediate elements. Thus, it is possible to write the well-known equation of the dynamics of the electric drive[7] for the elevator drive.

$$\mathrm{J}_{\text{пр}} \cdot \frac{\mathrm{d\omega}}{\mathrm{dt}} = \mathrm{M}_{\text{дв}} - \sum \mathrm{M}_{\mathrm{c}}, \quad (3),$$

where $J_{\text{пр}}$ — the moment of inertia of the system “motor–gearbox–drive pulley–ropes–cab–counterweight” reduced to the motor shaft, kg·m^2;

$M_{\text{дв}}(\omega)$ — the torque developed by the engine as a function of the angular velocity, N·m, this ratio is determined by the mechanical characteristic of the engine;

ΣM_c — the sum of the moments of resistance reduced to the motor shaft from the cab movement, counterweight, ropes and transmission losses, N·m.

In general,

$$\Sigma M_c = \sum_1^2 S_i \cdot r_{\text{к}} / i_{\text{ред}}, \text{ где} \quad (4)$$

S_i — force in the rope at the points of run-on and run-off from TSh, N, determined from formulas (1) and (2). In these formulas, r_k — radius of the traction sheave, m; $i_{\text{ред}}$ — gear ratio; ω — angular velocity of the motor, 1/s; t — current time, s.

From formulas (1), (2), (3) and (4), it follows that the instantaneous value of the total moment $M_{\text{дв}i}$ depends on the moment of inertia of the system $J_{\text{пр}i}$ reduced to the motor shaft, forces in the rope branches $S_{\text{п}1}$ and $S_{\text{к}1}$, which, in turn, are determined by a combination of the random variables M, L, S and γ presented earlier.

Along with that, in accordance with the work objective, it is required to establish the influence of all the components of the loads and the mode of their formation as a whole on the elevator servicing intervals. Do this requires determining the so-called representative equivalent load on the elevator, for example, torque $M_{\text{экв}}$, which will be the value that affects the maintenance program, primarily the frequency of maintenance. The conditional axis in the elevator drive system, relative to which $M_{\text{экв}}$, is calculated, does not matter in principle, because with the help of known

[10] Epifanov AP. Fundamentals of electric drive. St. Petersburg: Lan’; 2009. 192 p. (In Russ.)

reduction methods, the equivalent load can be recalculated to an arbitrary point. In this work, the main engine shaft is selected as the reduction point.

Elevator motor shaft torque as a function of time $M_{д.i}=f(t)$ at every single stage of movement — when calling or moving with passengers — is determined as a result of solving the differential equation (3).

The given moment of inertia of the system J_{npi} will be considered during this i-th cycle as a constant value equal to the sum of the moments of inertia of rotating and translationally moving masses: engine rotor $J_{дв}$, the gearbox including TSh, the cab with the load, the counterweight and the rope branches. Using the well-known rule of reduction of masses and moments of inertia, we obtain a ratio for calculating the reduced moment of inertia of the system in the i-th cycle of the elevator operation:

$$J_{прi} = J_{дв}K_{вр} + [Q_k + Q_п + Q_{пасп} \cdot \gamma_i + q_k \cdot n_k \cdot (N-1) \cdot h_{эт}]\frac{r^2}{i_p^2},$$

where $K_{вр}$ — coefficient that considers the rotating masses of the gearbox and TSh;

$Q_{пасп}$ — passport lifting capacity of the elevator, kg;

The sum of the moments of resistance $\sum M_c$, given to the motor shaft, when lifting the cab

$$\sum M_c = (r_к/i_{ред})\ (S_{k1} – S_{п1})\frac{1}{\eta_{ред}} \quad (5)$$

when lowering the cab:

$$\sum M_c = (r_к/i_{ред})\ (S_{п1} – S_{к1})\eta_{ред}. \quad (6)$$

To calculate the sum of the moments on the motor shaft, values S_{kl} and $S_{п1}$ must be substituted from formulas (1) and (2), taking into account the sign rule. Along with that, for the case of lifting the cabin with passengers — according to the formula (5), the sum of the moments will be positive, for the descent of goods (6) — negative. When lifting the cab, in formula (5), values S_{k1} and $S_{п1}$ should be substituted in the following form:

$$S_{k1} = \frac{(Q_i+Q_k)\cdot g+(F_k+F_г)}{\eta_б^2} + n \cdot q_{тк} \cdot (H - \Delta h) \cdot g;\ S_{п1} = [Q_п \cdot g – F_п] \cdot \eta_б + n \cdot q_{тк} \cdot \Delta h \cdot g.$$

When descending the cab, values $S_{п1}$ and S_{k1} should be substituted in formula (6) in the following form:

$$S_{п1} = [Q_п \cdot g + F_п] \cdot \eta_б + n \cdot q_{тк} \cdot \Delta h \cdot g, 0.$$

$$S_{k1} = \frac{(Q_i+Q_k)\cdot g-(F_k+F_г)}{\eta_б^2} + n \cdot q_{тк} \cdot (H - \Delta h)\, g.$$

In the latter case, the sum of the resistance moments $\sum M_c$, calculated from formula (6), will be negative, since S_{k1}>$S_{п1}$. When solving differential equation (3), it should be taken into account that the torque developed by the engine during start-up and after the end of start-up, $M_{дв} < 0$.

When solving differential equation (3), it is required to set the initial and final conditions. The initial conditions for all modes of movement with or without a load are the same: for t=0, φ=0, ω=0. As a result of solving the equation, we obtain a change in the moment on the engine shaft $M_{дв}$, the movement of the cab h (m), the angular velocity ω (rad/s) from time. Let us consider the solution to equation (5) to obtain time functions $M_{дв}$, h, t, ω.

The engine parameters and its mechanical characteristic $M_{дв}(\omega)$ are presented graphically in Fig. 5.

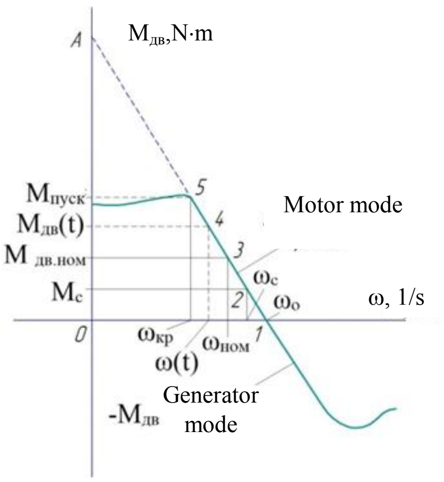

Fig. 5. Mechanical characteristic of an asynchronous squirrel-cage motor:
1 — ideal idle speed (synchronous angular velocity); 2 — corresponds to static load ($\sum M_c$) in motor mode;
3 — to engine load rating; 4 — to engine current state; 5 — to starting (critical) mode of operation

The process of movement in each cycle (with or without passengers, up or down) generally includes four stages (Fig. 6):

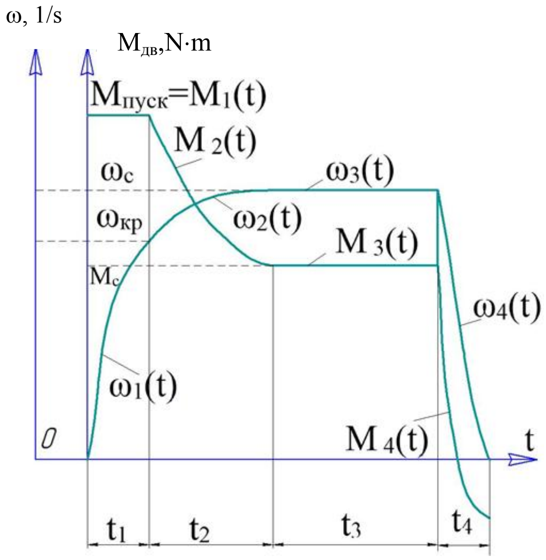

Fig. 6. Qualitative picture of change in angular velocity ω(t) and torque on the motor shaft $M_{дв}$(t) over the periods of the elevator movement

It is necessary to separately consider the solution to the equation when lifting the cab$\sum M_c > 0$ (motor mode) and lowering the cab $\sum M_c < 0$ (generator mode).

Motor mode. At the first stage, the torque developed by the engine is equal to the starting one, $M_{пуск}$. Its value is maintained throughout the first period$M_{дв}(\omega) = M_{пуск}$. Equation (3) takes the form:

$$J_{пр1} \cdot \frac{d\omega}{dt} = M_{пуск} - \sum M_{c1.}$$

Solving the differential equation, after the transformations, we get expressions for calculating the engine torque, the time of each stage, and the path traveled by the cab. For the first stage:

$$M_{дв1}(t) = M_{пуск}.$$

$$t_1 = \frac{\boldsymbol{J_{пр1}\omega_o^2(1-S_{кр})^2(1-S_{ном})}}{1000N_{дв}(\lambda_{пуск}-\lambda_c)}.$$

$$h_1 = = \frac{J_{пр.1}\cdot\omega_0^3\cdot(1-S_{кр})^2\cdot(1-S_{ном})\cdot r}{2000\cdot N\cdot(\lambda_{пуск}-\lambda_c)\cdot i_{ред}}.$$

At the second stage, the start-up continues from angular velocity $\omega_{кр}$ to angular velocity ω_c, corresponding to the moment of static load $\sum M_c$, i.e., on the segment $\omega_c \le \omega \le \omega_{кр}$ (Fig. 5 and 6). The movement occurs on the working section of the engine characteristic. The results of the solution and transformations on section 2:

$$M_{дв2} = M_{дв}(\omega_{ср}) = \frac{M_{ном}}{S_{ном}}\left(1-\frac{\omega_{ср}}{\omega_{ном}}\right).$$

$$t_2 = \frac{J_{пр}\cdot\omega_0^2}{1000N} S_{ном} ln\left[20\left(\frac{\lambda_{пуск}}{\lambda_c} - 1\right)\right];$$

$$h_2 = \frac{\omega_{ср}\cdot r_k}{2i_{ред}} t_2,$$

where $\omega_{ср} = \frac{\omega_0}{2}(2 - S_{кр} - \lambda_c S_{ном})$, $\lambda_{пуск}, \lambda_c$ – accordingly, the ratio of the starting torque of the engine, the static torque of the resistance to the nominal.

At the end of the second stage, the engine switches to the steady-state mode, the cab speed is determined from the formula:

$$v_2 = \frac{\omega_0\cdot r_k}{i_{ред}}(1-\lambda_c S_{ном}). \quad (7)$$

At the third stage, the system moves at a steady speed, which is determined from formula (7). To calculate the path of the third stage h_3 it is necessary to: calculate the height of the cab lifting (lowering) when calling or moving with passengers as the difference between the levels of floors (L–M)h or (M–S)h, where h – is the interfloor height;

determine the sum of the distances that the elevator passed at the first and second stages: h_1+h_2; calculate the path of the third stage: $h_3=(L–M)h–(h_1+h_2)$.

Thus, all the required relations for the power simulation of the elevator operation in the motor mode are obtained.

In the generator mode, when the cab with a load is lowering, $M_c<0$, the acceleration duration can be neglected. The system "motor – gearbox – TSh – ropes – cab –counterweight" switches to the generator mode in a short time, the engine creates a braking torque, rotating at super-synchronous speed. The descent speed is determined by the mechanical characteristic when substituted $M_{дв}=–M_c$ (Fig. 5):

$$v_{ген} = \frac{\omega_0 \cdot r_k}{i_{ред}}\left(\frac{M_c}{M_{ном}} S_{ном} + 1\right).$$

When calculating $M_c<0$ in formula (6) it is required to enter the efficiency of the gearbox into the numerator. Knowing $v_{ген}$, we can find, by analogy with the previous one, height $h_{ген}$ and the duration of cab lowering to height $Kh_{ген}$, where K — the number of interfloor spans traveled by the elevator.

The simulation of the power modes of the elevator was performed according to the program[11]. Figure 7 shows fragments of the results of modeling equivalent loads. The graphs show that the torque on the main engine shaft increases proportionally to the square of the number of floors of the house and depends significantly on the observation time.

Discussion. The issues of justification of the regulations for the maintenance of passenger elevator installations remain highly relevant. The essence of the problem is that the maintenance programs recommended in regulatory documents and used in practice do not take into account the actual loading modes of the main nodes in magnitude and in time. To reproduce the real modes of elevator installations operating under the impact of numerous random actions, the need and feasibility of simulation is proved.

The peculiarity of the obtained research results in comparison to the known normative and literary data is that the selection of a specific elevator is associated with correlation relations with the operating characteristics and the residual resource of the installation.

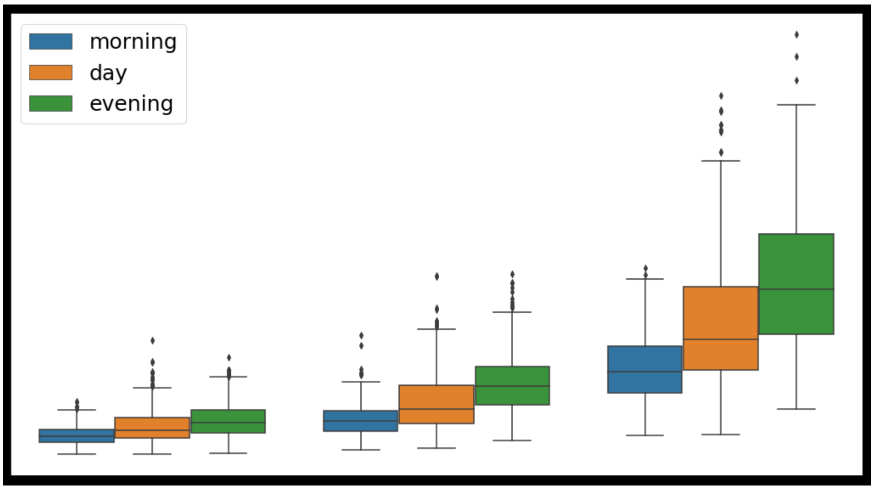

Fig. 7. Dependences of equivalent moment on the elevator engine shaft on the number of floors of a residential building (9, 16, 22 floors) and time interval of observations: morning, day, evening

Conclusion. As a result of the research, a complex indicator of the elevator load is proposed, taking into account the net operating time, the value of the equivalent load, the specific number of starts, and the degree of resource development. In accordance with the indicator value, the maintenance schedule is determined. Mathematical workflow models, including random impact distribution functions, have been developed, providing simulation modeling of elevator operating modes considering the random nature of influencing factors. The relations for calculating the static

[11] Otrokov AV, Khazanovich GSh, Apryshkin DS. Simulation of the passenger elevator operation: Certificate of software State registration no. RU 2018664988. Copyright holder: DSTU. 2018. (In Russ.)

and dynamic forces of the elevator drive are described in detail. Basic relations of the impact of the elevator parameters and operating conditions on the power and kinematic parameters of the elevator installation are obtained.

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D. S. Apryshkin: research objectives, tasks and program formulation; output of mathematical models; design of the graphic part. G. Sh. Khazanovich: generation of the concept of elevator maintenance; verification of the basic operating modes of elevator installations; selection of influencing factors; consultations when developing mathematical models. O. V. Gutarevich: description of the elevator installation operation; selection of materials for the analysis of the issue; participation in the analysis of the operation modes of elevator installations.

All authors have read and approved the final manuscript.