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Rope-free elevator system based on planar positioners for vertical and horizontal transport

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1. Introduction

In the modern world, ever taller buildings occupying ever greater surface area are being built. In large, urban agglomerations, due to very high and rising prices of construction lots, developers are deciding to built large, high-rise public buildings (libraries, offices, shops, etc.) as well as residential buildings that may have more than 100 storeys. It is becoming necessary to apply ever newer technologies as well as materials that are light, strong, and aesthetic at the same time to build them. This is all aimed at ensuring that buildings can face e.g. increased wind pressure and other atmospheric factors, tectonic movements of the subsoil on which they are founded, or in new solutions – a potential terrorist attack.

Despite continuous progress in this field, elevator design essentially remains the only unchanging thing since its invention and implementation. During the construction phase of a building, elevators serve to transport construction teams and materials between storeys. After public or residential buildings are commissioned for use, elevators serve to transport people, goods, products, or even cars. Of course, modern elevators differ on the exterior from those that were first invented and used in the XIX century, however the principle of operation remains essentially unchanged. This principle is the movement of cabins between storeys of buildings on the vertical plane with the application of load-bearing tension members (lines, chains) [1, 2]. As a rule, after being transported to a specific level, people must travel the remaining distance to rooms on the floor on their own. Additional equipment is usually used for horizontal transport, e.g. moving sidewalks or individual shafts with cabins moving horizontally. In relation to the above, it seems purposeful to develop modern elevator designs that simultaneously serve for vertical and horizontal transport, and whose movement within the building is not limited by the design of individual shafts.

This article presents an original solution of a rope-free elevator for vertical and horizontal transport. The basis for creating this innovative elevator solution is a drive utilizing planar positioners with aerostatic bearings. The advantages of applying such a solution in modern, large-surface, multi-storey residential and public buildings are also indicated. Directions of further research are indicated in the summary of the article.

2. Selected modern elevator solutions

When designing modern high-rise buildings, the placement and number of communication routes, transport channels, and potential evacuation routes for the persons using them must be planned. Even in the case of a large number of persons using means of transport at the same time, arrival at a given storey must not entail a long waiting time. Currently applied elevator solutions with a machine room and traditional vertical shaft are therefore insufficient. For this reason they may create many engineering problems when planning the architecture of new skyscrapers. In article [3], problems that may be encountered during the designing and operation of elevators (including types and lengths of ropes used, vibrations during movement and the problem of cabin rocking during movement at high speeds, the types of drives used in the design, as well as the very important issue related to safety of elevator use) were presented. Due to its mass and vertical vibration a steel rope causes problems in elevators for skyscrapers [4].

By analysing the results of certain studies conducted around the world in the scope of designing new elevator solutions [4-9], one can observe that engineers are focusing on developing rope-free systems to eliminate the problems listed above. In most of these studies, the authors mainly focus on researching new algorithms for controlling elevator systems in multi-storey buildings. Direct drive linear motors are the drive used in laboratories and prototype elevator research systems. It has been demonstrated that they can solve problems that arise when a rope is used as the tension member driving the elevator cabin. However cabin movement remains restricted by the shaft walls, and it can only be horizontal or vertical.

Information concerning an innovative design by the ThyssenKrupp company in Germany, with the commercial name MULTI [10, 11], appeared in the media at the end of 2014. In the proposed solution, the cabin moves on both the horizontal and the vertical plane. The solution is based on linear motors and utilizes the phenomenon of magnetic levitation. According to reports, this solution may revolutionize the elevator system used until now.

However, none of the proposed solutions for transport systems does not provide simultaneous integration of movement in two directions for a single elevator cabin, besides movement in the vertical and horizontal lanes.

3. Description of the original rope-free elevator system

The proposed original solution for horizontal and vertical movement of the cabin is dedicated, above all, for newly built buildings. As early as during the stage of designing the body of the building, the location and proper dimensions of the shaft must be planned with consideration of the guiding surfaces over which the cabin moves.

Depending on the needs, surface area, and number of storeys of the building, as well as the number of rooms to which cabins may travel, an elevator can have a single cabin or multiple cabins. Fig. 1 presents a rope-free multi-cabin elevator for horizontal and vertical transport with guiding surfaces on all shaft walls. This solution makes it possible for the cabin to move over all shaft walls and thus travel to any room in the building.

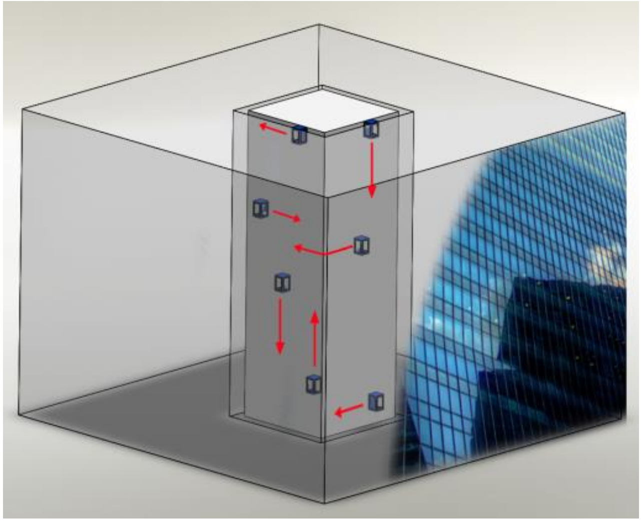

Fig. 1 Perspective view of the rope-free multi-cabin elevator for horizontal and vertical transport [12]

Designing of an elevator in the configuration presented in Fig. 1 requires the following preliminary assumptions to be made:

- the elevator is rope-free – there is no need to install a machine room or lines on which elevator cabins would be suspended in shafts;
- the elevator's drive is based on a planar positioning system built of XY electromagnetic modules of the forcer separated by an air cushion from an immobile stator;
- the walls of the building's shaft (core) contain guide surfaces that form the track for elevators to move over vertically and horizontally;
- guide surfaces made of steel plates with a toothed structure superimposed on them constitute the stator modules of the planar positions; at the same time, they can be considered to be the load-bearing elements of the entire structure;
- elevator movement over all shaft walls is permitted;
- drive forcers will be situated on the exterior walls of the elevator's cabin; they may constitute a part of the cabin's structural components;
- each elevator must have its own source of compressed air, which is necessary for generating an air cushion between the stator's components and forcer of planar drives;
- elevator control is carried out by means of a wireless telemetric system, which will contribute to limitation of wired connections and conflict-free movement on both the horizontal and vertical plane;
- master SCADA software enabling management of collision-free cabin movement and security of the elevators system should be coupled to the telemetric system.

4. Elevator's drive system

Components of the rope-free elevator with a single cabin for vertical and horizontal transport have been presented in Fig. 2 in a basic configuration. The elevator's drive employs a planar positioning system. The main components of the planar positioning system are immobile stator blocks *1* installed on the shaft surface *2* and mobile forcer blocks *3* installed on the exterior side surfaces of the cabin *4*. Stator blocks *1* constitute the track distributed over the shaft surface *2*. This track makes it possible for the cabin *4* to move horizontally and vertically to doors *5* of specific rooms and doors of the building's corridors. The cabin *4* moves over the shaft *2* without coming into contact with it thanks to the application of aerostatic bearings (aerostatic lubrication). An air cushion (air gap) is generated between forcers *3* and stators *1*. Power supply to the cabin is realized by means of a traction network *6* positioned along the track of cabin *4* movement.

During passage of the cabin *4* from wall *a* to wall *b*, forcers *3* on the cabin's surface are activated and interoperate with stators *1* located on wall *b* (Fig. 2). Next, the forcers *3* currently interoperating with stators *1* located on wall *a* are deactivated. Thus, when the cabin *4* is pulled by wall *b*, it pulls away from wall *a*.

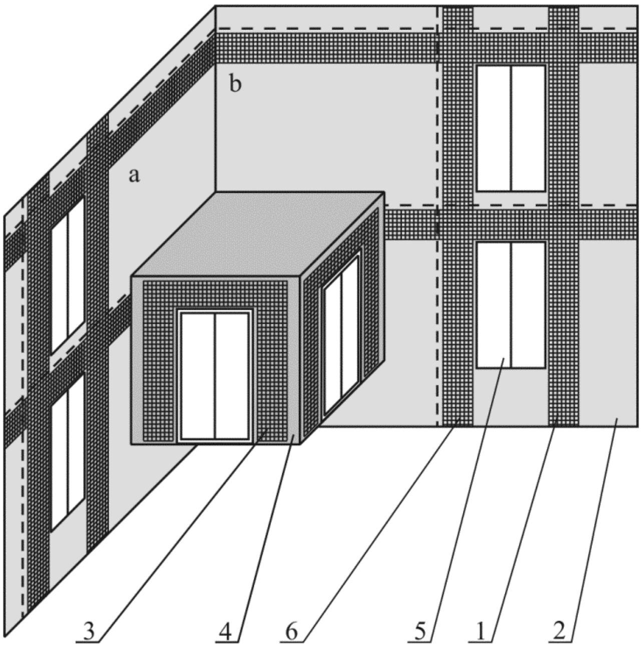

Fig. 2 Basic components of the rope-free elevator for vertical and horizontal transport

Depending on the building's transport needs, it is possible to place the cabin's track arbitrarily. Stator blocks can also be distributed over the entire shaft surface, enabling cabin movement in two directions simultaneously on each wall of the shaft. This solution will make it possible to shorten the route of travel to individual doors and reduce the time of cabin travel to the target location.

The basic forcer consists of: an aluminum frame, electromagnetic modules, and a pneumatic system supplying the stator-forcer system with compressed air. The pneumatic system generates the air cushion. The pneumatic system installed on the elevator's cabin consists of an pneumatic compressor, a compressed air preparation unit (reducer, filter), a conduit leading air to supply openings (nozzles, load-bearing chambers), and grooves distributing air along the load-bearing surface.

The load-bearing surface of a single forcer (Fig. 3) contains nozzles *1*, load-bearing chambers *2*, distributing grooves *3*, and two groups of orthogonal electromagnetic modules I and II which are responsible for the forcer's movement relative to the stator and attraction of forcer to the stator. Modules I are responsible for moving the forcer along the X axis, and modules II – along the Y axis.

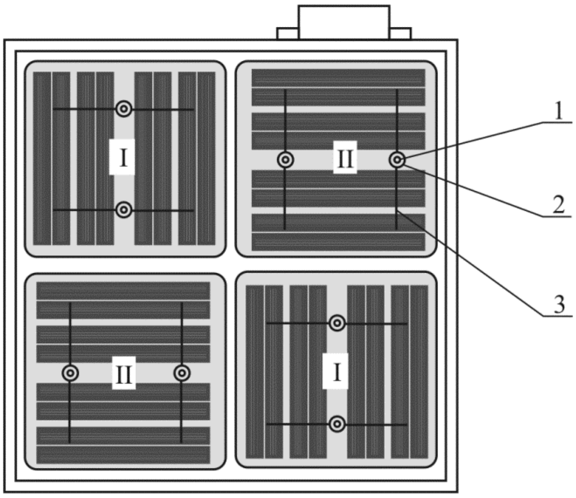

Fig. 3 Load-bearing surface of the forcer mounted on the elevator cabin

Due to the shape of the load-bearing chamber and the working surface of the forcer, centrifugal (divergent) spatial flow (Fig. 4, a; Fig. 4, b) and parallel flat flow (Fig. 4, c) are distinguished [13].

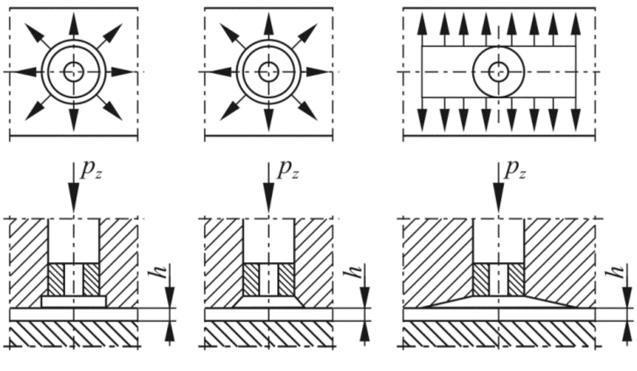

Fig. 4 The shape of load-bearing chambers: a - with a tapered cross-section (cylindrical); b - with a variable cross-section (conical-circular); c - with a variable cross-section (convergent-rectangular); p_z – pressure supply, *h* – height of the air gap [13]

Air-distributing grooves are intended for distribution of compressed air over the entire load-bearing surface of the forcer. Fig. 5 shows numerical simulation of the distribution of the air pressure p in the stator – air gap – forcer system with distributing grooves (Fig. 5, a) and without distributing grooves (Fig. 5, b). Computer simulation was worked out in the computer program Comsol Multiphysics. Computer simulation results were obtained for the following input data: load-bearing surface dimensions $l_x = l_y = 0.146$ m; height of the air gap $h = 4\times10^{-6}$ m; height of the distributing groove $h_g = 0{,}15\times10^{-3}$ m; pressure in the load-bearing chamber $p_k = 4\times10^5$ Pa; atmospheric pressure $p_a = 1\times10^5$ Pa.

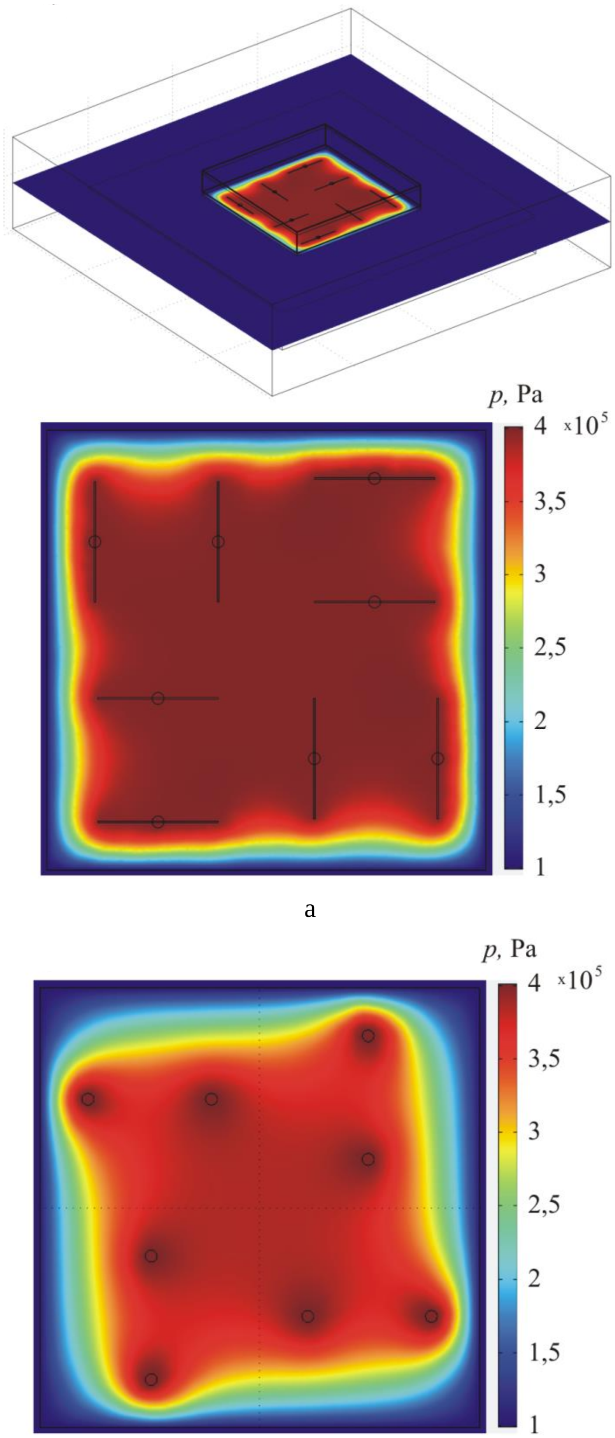

Fig. 5 Distribution of the air pressure *p* in the stator – air gap – forcer system: a - with distributing grooves; b - without distributing grooves

The contour of the cross-section of grooves is predominantly triangular (Fig. 6). This is linked to the pursuit of a flow channel with the highest ratio of flow cross-section to perimeter. An angle of the grooves' contour of 60° or 90° is accepted [13].

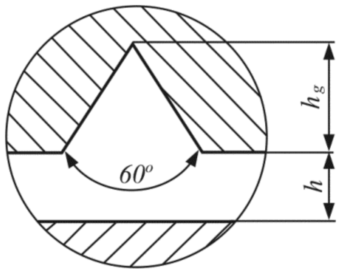

Fig. 6 Cross-section of the distributing groove: h - height of the air gap; h_g - height of the distributing groove

Fig. 7 presents the drive system, built on the basis of two single-phase modules 1, 2 in a layer. The elementary electromagnetic module consists of two magnetic cores a, b, between which a permanent magnet c is found. A coil is located on every core (A for module 1, B for module 2). Cores have teeth found at such a distance from one another that they correspond to the pitch of the stator's teeth.

Two magnetic circuits are distinguished in every elementary electromagnetic module (Fig. 7). The first circuit, in which magnetic flux Φ_m is generated by the permanent magnet, and the second circuit, in which flux Φ_c is generated by a coil with n turns. Flux Φ_c generated by the coil, generates force F, causing movement of the drive module (and thus movement of the forcer relative to the immobile stator along the x axis – F_x and y axis – F_y). Flux Φ_m, generated by the permanent magnet, generates a force of magnetic attraction F_p of the forcer to the stator.

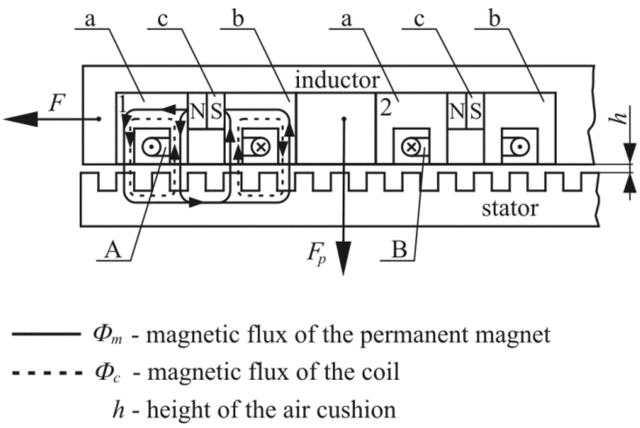

Fig. 7 Elementary drive module

Fig. 8 presents the principle of operation of drive modules enabling movement of the forcer relative to the stator. Only one coil, A or B (coil of elementary module 1 or 2), is activated in a given unit of time. Coil A was activated in the first step. The teeth of module 1 are positioned opposite (on the axis) to the teeth of the base (teeth of N poles are positioned opposite to base teeth, teeth of S poles are positioned between base teeth). The teeth of elementary module 2 are offset relative to the teeth of module 1 by ½ tooth. Deactivation of coil A and activation of coil B causes movement of the forcer relative to the stator by one step. The teeth of module 2 are positioned opposite to (on the axis of) base teeth. The teeth of elementary module 1 are offset relative to the teeth of module 2 by ½ tooth.

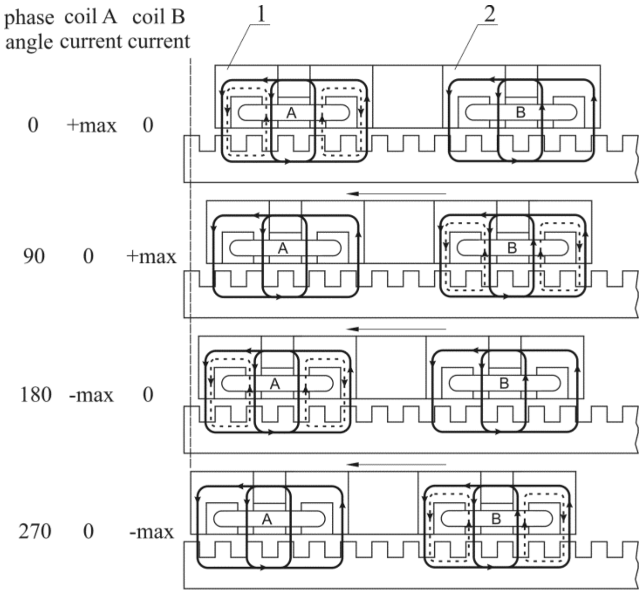

Fig. 8 Principle of operation of the drive module [14]

In the same manner, further alternating activation of coil A or B causes movement of the forcer relative to the stator by successive steps [14, 15].

5. Control system of the rope-free cabin system

The control system of the rope-free cabin system consists of, among other things: control cards responsible for movement of individual cabins; a wireless telemetric system; a computer system with SCADA software monitoring collision-free cabin movement on the vertical and horizontal plane. Input automation components are: buttons for calling individual cabins and buttons installed in cabins, integrated with an HMI operator's panel, serving for selection of the target location; Hall sensors reading the cabin's current position relative to the shaft surface; and g-load sensors indispensable for ensuring comfortable and uniform movement of passengers. The position of individual cabins in the three-dimensional space of the shaft is visualized on HMI operator's panels installed near individual entries into cabins and inside of individual cabins.

Control of cabin movement is performed by the control card, which, according to the control program, processes the digital signal from the computer to an analog current signal – a series of current impulses with specific parameters: frequency, period, and pulse-duty factor. Next, the series of current control pulses is directly transformed into a series of linear shifts $(\Delta x, \Delta y)$. The cabin's movement speed depends on the frequency of supplied impulses, and the value by which the cabin will move relative to the shaft surface depends on the number of supplied pulses.

A broader description of the design, principle of operation and control of planar positioners used to build the shift system can be found in articles [16, 17].

Fig. 9 presents the laboratory stand with the planar positioning system. The elevator cabin *3* is mounted on the forcer *1*. The main aim of the research was the confirmation of the capability of applying planar positioning systems to the drives of the rope-free elevators. The capability of applying the forcer – air gap – stator system in vertical working position has been tested.

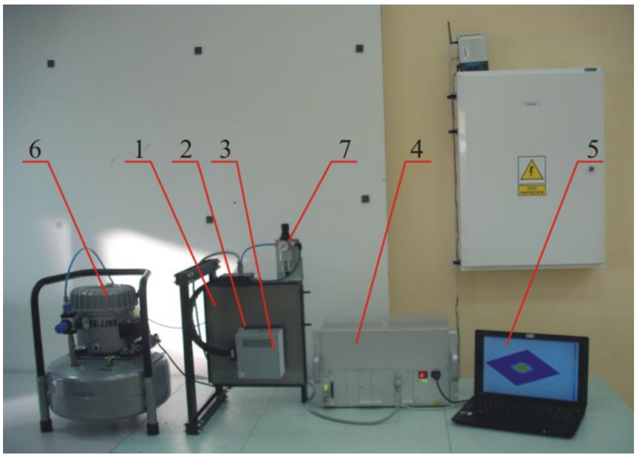

Fig. 9 Laboratory stand: *1* - immovable stator (platen); *2* - forcer with gas-film lubrication (aerostatic lubrication); *3* - cabin; *4* - controller; *5* - personal computer (interface RS232, Step/Dir); air source: *6* - air compressor, *7* - air filter and regulator

6. Advantages of the rope-free elevator system

Compared to existing design solutions of elevators on the market, the proposed system has indisputable advantages, that may bring new quality to intra-building transport of persons and objects. Among them, the following deserve special attention [18]:

- the elevator is rope-free;
- transport can take place vertically and horizontally as well as in two directions of movement simultaneously;
- there is no need to lubricate guides periodically, which translates to limitation of activities related to servicing the system and reduction of maintenance costs;
- in the event of an emergency related e.g. to a loss of electrical or pneumatic power supply, required for generating an air cushion, the elevator will not fall thanks to the strong rare earth magnets applied in the design of stators; the cabin will be pulled to the shaft wall, where it will remain in safety until the problem is solved by technical teams;
- a multi-cabin system with the capability of configuring cabins moving in one shaft, allowing for quick and flexible reaction to actual transport needs within a given large-area building;
- utilization of Hall sensors built into the drive allows for very precise and repeatable control of elevator cabin positioning in a feedback loop;
- depending on the actual need (transport of people or goods), the speed and acceleration of cabin movements can be chosen appropriately;
- no mechanical gears and no need to build a machine room in the building, meaning even more space for offices, storage rooms and residences;
- in addition, purified air used to generate the cushion separating stators from forcers can be used as an additional ventilation system for the building;
- capability of achieving greater movement speeds compared to typical solutions due to the lack of the air cushion effect, resulting in resistance during vertical movement of a cabin in a standard shaft.

7. Conclusions

1. The innovative solution of an elevator moving vertically and horizontally is innovative due to the use of coordinate planar positioners as the drive source.

2. The advantages of this solution are:

- easy construction;
- capability of achieving two degrees of freedom using a single moving part;
- capability of building mechanisms (manipulators) with a series, not parallel, kinematic structure;
- the friction between inter-working surfaces is low enough that arising forces are negligible;
- high precision of positioning;
- capability of reaching large working spaces;
- capability of building systems with multiple supports on a single base;
- free choice of installation position in space – the forcer can be mounted in vertical orientation; the capability of applying planar positioners has been indicated in numerous designs and implementations [19-23].

3. The forcer moves without contact over the immobile base thanks to the application of aerostatic lubrication. The application of compressed air as a lubricant practically eliminates frictional resistance in the system (friction coefficient $\mu = 10^{-4} \div 10^{-5}$ which is the primary cause of relaxation oscillations (stick-slip phenomenon)) [13, 24].

4. In the future, the presented system may be implemented in newly built, high-rise public and residential buildings.

5. Within the framework of further work on the design of the rope-free elevator system, expansion of the research laboratory station to an extent enabling testing of the programs responsible for controlling the system, studying the behaviour of cabins under varying loads in dynamic conditions, and assessment of vibration damping by the air cushion separating stators from forcers, is planned.

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ROPE-FREE ELEVATOR SYSTEM BASED ON PLANAR POSITIONERS FOR VERTICAL AND HORIZONTAL TRANSPORT

S u m m a r y

An original solution of a mechatronic rope-free elevator is presented in the article. The elevator cars in the proposed solution can travel in the shaft both vertically and horizontally, as well as in the two directions simultaneously. The elevator drive is based on a mechatronic planar positioning system with an aerostatic bearing. The conceptual solution of elevators used in vertical and horizontal transport is also presented in the work. The principle of operation of the mechatronic planar positioning system with the aerostatic bearing is explained. The directions of further studies are outlined.

Keywords: elevator, rope-free elevator, vertical and horizontal elevator, planar coordinate positioning system, planar positioner.

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