Vertical Movement of Resonance Hopping Robot with Electric Drive and Simple Control System

T. Akinfiev, M. Armada and H. Montes

***Abstract*—In the paper vertical movements of resonance hopping robot with one leg and electric drive are considered. Special construction of hopping robot with compensation of losses during flight of the robot allows to employ a relatively simple control system as well as to get a stable regime of its operation. The designed robot has self-properties to maintain a specified height of jumping even with simple control system. Results of dynamical calculations, simulations and experimental testing are presented.**

***Index Terms*—Robotics, resonance hopping robot, oscillations, stability of movement.**

I. Introduction

Usually, hopping robots with electric motors have elastic devices that save part of energy in the moment, when the velocity of the robot is equal to zero; a motor compensates energy losses when robot's leg and a bearing surface have a contact [1-4]. In the absence of the contact the drive motor cuts off. Under such control it is necessary to use a relatively powerful (and consequently, rather heavy) electromotor, which is capable to realize a compensation of losses during a very short time of the contact of robot's leg with a bearing surface.

Taking into account that the time of the contact is about ten times less than a complete cycle time, it seems to be advantageous to make a compensation of losses during robot's flight time and not during the time of the contact of robot's leg with a bearing surface [7, 8, 9]. Such approach allows to use a motor of a considerably lower power, that gives in significant decrease of robot's weight and thus a consumption of energy is dimished.

Another possibility related to decrease of energy consumption consists in minimizing of energy losses (including losses derived from rubbing together of a leg and a body of the robot, losses inside resilient member etc.) during robot movement. However, this method does not necessarily give satisfactory results. Thus, in the paper [5] it is shown that in some cases the capacity factor of energy of a compressed spring could constitute only 20 %.

Additional problem, connected with a provision of a stable robot operation, is that hopping robot represents a highly nonlinear system (even using linear resilient members) characterized by existence of shocks. As a result, in such systems there can appear bifurcation effects and even strange attractors [6]. In this case a provision of a stable operation of the robot is usually reached at the expense of rather complicate control system.

In the paper [8] it is shown that under certain conditions, hopping robot can maintain self-stabilization without any sensor. However, in this paper a simplified robot model is considered (a negligibly small mass of leg, ideal spring). In the present paper a special construction of hopping robot [9] is considered with compensation of losses during flight of the robot. This robot has been designed in Industrial Automation Institute (Madrid, Spain) and allows to employ a relatively simple control system as well as to get a stable regime of robot's operation. In the present paper energy losses inside the spring and shock interactions of robot's leg with its body and bearing surface are considered.

II. Concept of Robot Operation

A kinematic configuration of a robot under consideration is shown in Fig. 1. The robot has a body in which a leg with a mechanical stop block is anchored with a possibility of a forward movement.

A spring is installed between the body and the leg of the robot. A motor-reducer is connected to a control system and is fixed on the body of the robot. On the output shaft of the motor-reducer a cylinder is fixed, which is connected to the leg of the robot through a flexible rope. A control system can contain different sensors, but in the elementary version it is enough to use only two sensors: angle sensor of rotational displacement of a motor and a sensor of a contact of the leg and the bearing surface.

The operation of the robot is carried out in a cyclic way without stoppage in an extreme lower position. Let us denote a

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number of a cycle by i. Let us assume also that in initial position robot is at a maximum height above the bearing surface. Its gravity center has a height H_i counted from a position of the robot that corresponds to the moment of a contact of the leg with the bearing surface.

During robot's flight the drive motor turns through some angle a cylinder that is joint with the robot. The turn begins from the moment of the robot's leg separation from the bearing surface. This leads to a reeling of a rope on the cylinder and, as a consequence, to a partial tightening of a spring. When the before given strain deformation l is reached, the drive motor stops to rotate the cylinder and holds it in this position. The process of a tightening of the spring should be terminated not later than the leg of the robot makes a contact with the bearing surface. After a signal is obtained from a sensor of contact of the robot's leg and the bearing surface, the drive motor turns the cylinder in the opposite direction the same angle. Thus, the rope ceases to interact with the robot's leg.

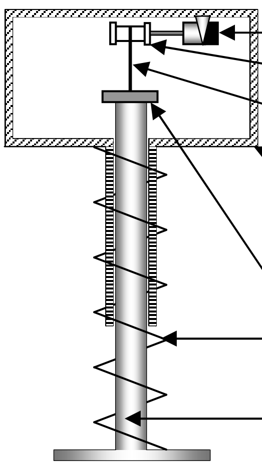

Fig. 1. Kinematic configuration of a hopping robot with a compression spring.

At the moment of a contact of robot's leg and bearing surface the leg stops, and the robot's body, having certain velocity, continues moving downwards and deforms the spring additionally. The body of the robot after a stopping in the lowermost position starts to move up under a compressed spring action. This process lasts up to the moment when the stop block of a leg impacts the body of the robot. Furthermore, the free flight of the whole robot continues until it reaches maximum height H_{i+1}. Then the whole process repeats. The obvious condition of a stable operation of the robot is:

$$H_{i+1} = H_i \tag{1}$$

For fulfillment of this condition, an amount of energy, equal to energy losses during a motion cycle, is to be transferred to a spring by the drive motor.

III. Mathematical description

When equations that described robot's movement during the cycle number i were set up, the following assumptions were used:

- the bearing surface was considered absolutely solid,
- the leg impact upon the bearing surface was considered as instantaneous and absolutely inelastic,
- the impact of a leg stop block upon robot's body was considered as instantaneous and absolutely inelastic,
- a resilient element was considered as linear; however, for calculating of power loss during relative movement of the leg and the body of the robot and during the corresponding deformation of the resilient element, it was accepted, that at loading of the resilient element it was characterized by a spring constant c_1 and at unloading - by spring constant c_2, and that $c_1 > c_2$,
- it was supposed, that the spring was strainless in a position, when the stop block of the leg was in contact with the body of the robot (leg of the robot is extended as much as possible),
- m was defined as a sum of a mass of robot's leg and a half of a mass of resilient element,
- M was defined as a sum of a mass of the body of the robot, a mass of all elements rigidly connected with the robot and a half of a mass of resilient element.

On the base of a mechanical energy conservation law we have [for the robot movement from initial position (Fig. 2a) into a position immediately before the impact of the leg of the robot against bearing surface (Fig. 2b)]:

$$V_{1i} = \sqrt{2gH_i} \tag{2}$$

where V_{1i} is a velocity of the robot before robot's leg impact against bearing surface, g is gravitational acceleration.

On Fig. 2b, 2c the process is represented of the impact of the robot' leg against bearing surface (2b – a position immediately before the impact, 2c – a position immediately after the impact).

Taking into consideration that the impact is instantaneous and absolutely inelastic, it is evident that a velocity and a position of the body of the robot during the impact do not vary, and the velocity of the leg ends up as null. Let us notice, that during this process the system loses energy, which can be calculated by the formula:

$$W_{1i} = \frac{mV_{1i}^2}{2} \tag{3}$$

On Fig. 2c, 2d a movement of the body of the robot is shown from the moment of the contact of the leg with the bearing surface up to the moment of full stop of the robot's body. From a mechanical energy conservation law we have:

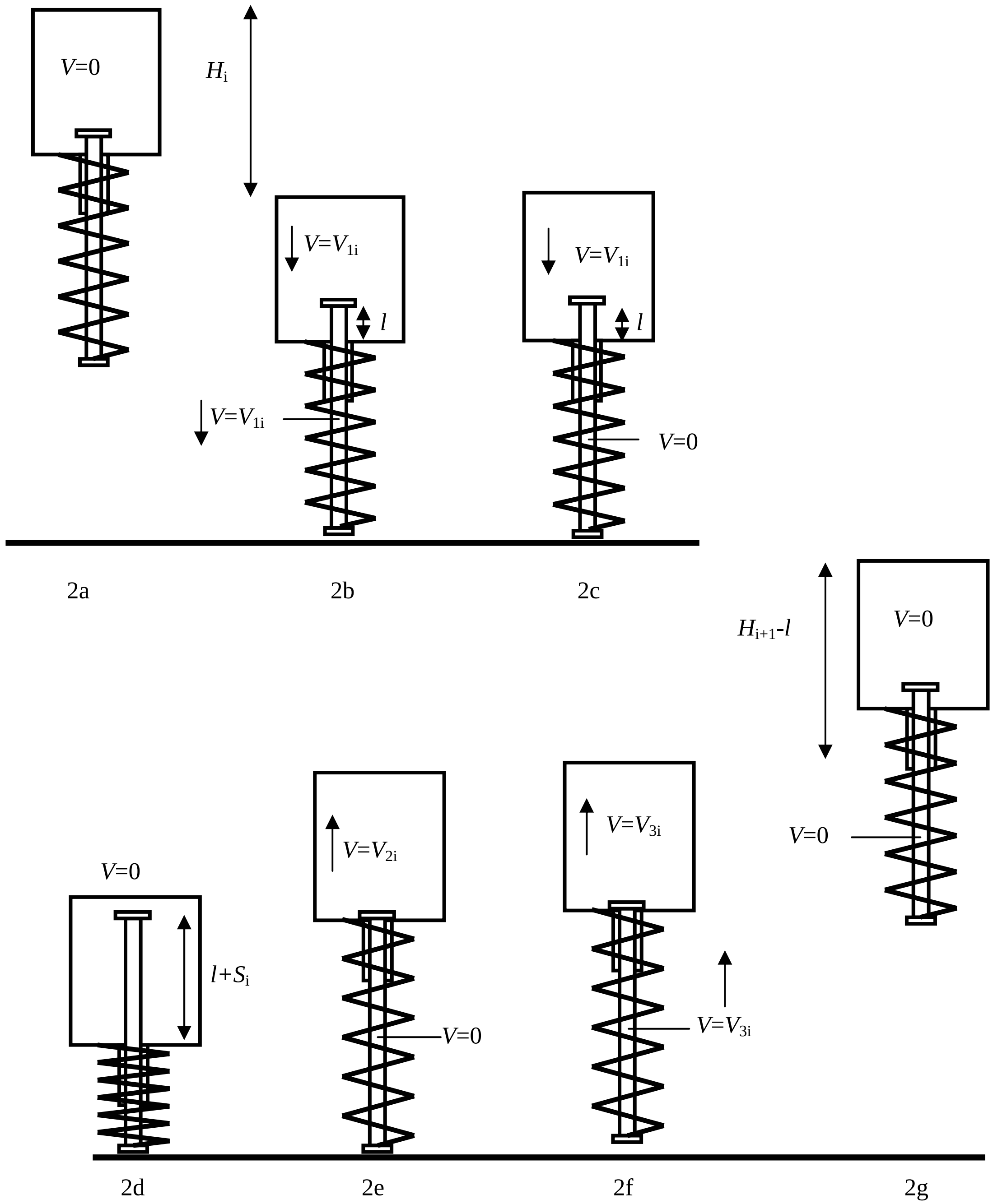

Fig. 2. Movement's cycle of hopping robot.

$$MgS_i + \frac{MV_{1i}^2 + c_1 l^2}{2} = \frac{c_1 (S_i + l)^2}{2} \quad (4)$$

where S_i is a magnitude of displacement of the body of the robot before full stop.

On Fig. 2d, 2e a process of displacement of the robot is shown from the lowermost position up to the moment, when the stop block of the leg is found in immediate proximity with the body of the robot (a position immediately before the impact). On the base of a mechanical energy conservation law, for this displacement we have:

$$\frac{c_2 (S_i + l)^2}{2} = \frac{MV_{2i}^2}{2} + Mg(S_i + l) \quad (5)$$

where V_{2i} is a velocity of the robot's body immediately before the impact of the leg stop block against the body of the robot.

On Fig. 2e, 2f the process of impact is shown of a stop block of a leg against the robot's body (2e – a position immediately before impact, 2f – a position immediately after impact). Considering that the impact is instantaneous and absolutely inelastic, to calculate a velocity of the robot after the shock it is necessary to use a law of conservation of momentum of the body:

$$MV_{2i} = (M + m)V_{3i} \tag{6}$$

Let us notice that during this process and because of inelasticity of the shock, the system loses the amount of energy, which can be calculated by the formula:

$$W_{2i} = \frac{MV_{2i}^2 - (M + m)V_{3i}^2}{2} \tag{7}$$

On Fig. 2f, 2g the last stage of a movement cycle of the robot is shown (2f – a position of the robot immediately after an impact of the leg stop block against the body of the robot, 2g – a position, when the robot has lifted on the maximum height). For this movement, on the base of the mechanical energy conservation law, we have:

$$\frac{V_{3i}^2}{2} + gl = gH_{i+1} \tag{8}$$

Let us mark, that during a whole cycle, the energy is lost in the resilient element:

$$W_{3i} = \frac{(c_1 - c_2)(S_i + l)^2}{2} \tag{9}$$

Thus, the total energy whole cycle losses, which should be compensated at steady-stated movement of the robot with the help of the motor, can be calculated by the formula:

$$W_i = W_{1i} + W_{2i} + W_{3i} \tag{10}$$

Provided the fulfillment of the condition (1), the set of equations (2, 4, 5, 6, 8) allows to find parameters of steady-stated driving of the robot. So, having set a required height of the flight of the robot, it is possible to find the magnitude of a displacement, on which the motor should move robot's leg during the flight time of the robot.

From the set of equations (2, 4, 5, 6, 8) it follows that for each steady-stated height H of robot's jump there exists the unique magnitude of spring displacement l, which provides the given height of jump. However, not for any magnitude of l it is possible to have a situation when robot makes jumps with a release from a surface. For the movements with a release from a surface a condition $l > l^*$ has to be fulfilled, where l^* is calculated from the equations (2, 4, 5, 6, 8) on the base of obvious condition $H_i = H_{i+1} = 0$.

The same set of equations allows to describe the process of damped oscillations of the robot with disconnected motor. For this purpose it is enough to set an initial height of lift of the robot and to assume that $l = 0$. Robot's jumping (with a leg separated from a surface) ends at the cycle number *n*, on which, instead of the equation (5), the inequality:

$$c_2 S_n < 2Mg \tag{11}$$

will be fulfilled for the first time.

IV. Stability of Motion

From a system of the recurrence equations (2, 4, 5, 6, 8) it follows, that the process of steady-stated movement of the robot is stable in relation to both low and high level of disturbances provided that on each cycle the drive motor transmits to the system the same amount of energy (i.e. extends a spring the same magnitude l). So, at random disturbance, which diminishes a height of jump of the robot, the losses are diminished also during the movement, according to the equations (3, 7, 9, 10), that gives in restoring of stationary height of jumps of the robot. Similarly, at random disturbance, which augments a height of jump of the robot, the losses also increase during the movement that gives in stabilization of a steady-stated movement (shown in Fig.3).

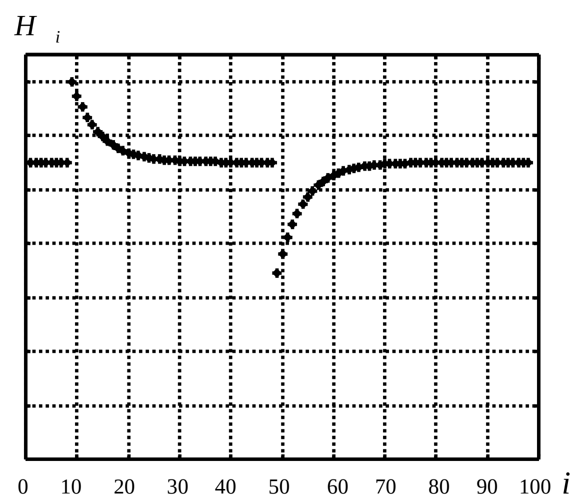

Fig. 3. Values of height of jumps vs. number of jumps (simulation). Jumps number 1-9 correspond to a steady-state movement. Significant disturbance with positive energy acted at the moment of jump number 10, significant disturbance with negative energy acted at the moment of jump number 50. Movement is self-stabilized because thesystem is working with 50% of reserve of stability.

It is necessary to notice, that the above mentioned is valid only in the case, when it is precisely known, that the magnitude of energy, provided by the motor, remains constant and does not depend on random disturbances. It is also very essential, how the process of displacement of a spring is carried out during the flight of the robot. It has been mentioned earlier, that this process should start at the moment, when the stage of the flight starts and should end before the leg's impact against surface, i.e. the process takes a quite determinate time T_C, which should not be greater than the flight time calculated by the formula:

$$T_F = \sqrt{\frac{2(H-l)}{g}} + \sqrt{\frac{2H}{g}} \tag{12}$$

However, if the process of displacement of the spring is finished accurately at the moment of the end of the stage of flight ($T_C = T_F$), the process of movement can be both unstable and stable.

The matter is that at random disturbance that diminishes a height of flight, the time (during which the motor transmits energy to the spring) is diminished also. Apparently, this time is not enough for the motor to be able to move the spring the required magnitude. As a result, the height (as well as the time) of the following jump will decrease. Furthermore, the process repeats.

To generate a certain reserve of stability of movement it is necessary to conclude a process of spring displacement a little earlier than the process of flight is finished. However, provided that the transmission is not self-braking or the motor is not supplied with the special brake, the motor consumes additional energy to hold the spring extended, so that too big stability reserve leads to non-rational energy expenses.

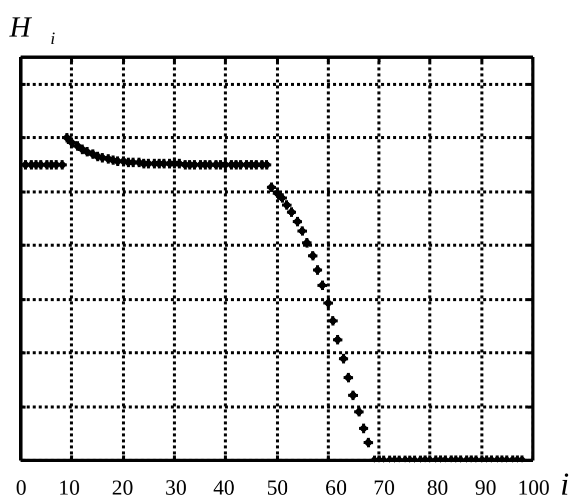

Fig. 4. Values of height of jumps vs. number of jumps (simulation). Jumps number 1-9 correspond to a steady-state movement. Disturbance with positive energy acted at the moment of jump number 10, disturbance with negative energy acted at the moment of jump number 50. The system is working without a reserve of stability, but with a feedback according to the formula 13 with a parameter N>1. The movement is unstable.

It is possible to provide a stabilization of robot's movement even under a condition $T_C = T_F$. In this case a feedback can be introduced in relation to the time of robot's flight. Thus, for example, supposing that the magnitude of displacement of spring caused by motor is not constant and depends on the magnitude of time of preceding cycle

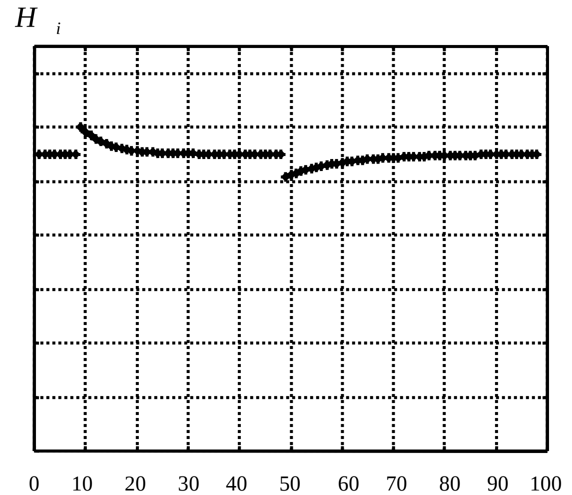

Fig. 5. Values of height of jumps vs. number of jumps (simulation). Jumps number 1-9 correspond to a steady-state movement. Disturbance with positive energy acted at the moment of jump number 10, disturbance with negative energy acted at the moment of jump number 50. The system is working without a reserve of stability, but with a feedback according to the formula 13 with a parameter 0<N<1. The movement is stable.

$$l_{i+1} = \begin{cases} l & \text{if } T_C < T_F \\ l * \left(\dfrac{t_i}{T_F}\right)^N & \text{if } T_C = T_F \end{cases} \tag{13}$$

we have that the movement becomes stable even in relation to significant disturbances under a fulfillment of a condition $0 < N < 1$ (Fig. 5). At $N > 1$ a movement is unstable (Fig. 4) in relation to disturbances that decrease the height of robot's jump; however, a movement is stable in relation to disturbances that increase the height of robot's jump. For realization of the condition (13) it is necessary to establish a corresponding law of control of the motor, which performs a displacement of the spring.

V. Experiment

For experimental testing of obtained results a laboratory prototype of a hopping robot was designed, manufactured and tested according to the scheme presented on Fig. 1. The prototype is designed to jump up to 0.4 m, has a weight 3,5 kg and the weight of its leg is 0,15 kg. First experiments have shown, that without upload of energy from the motor, about 50 % of energy accumulated in the spring is lost during the first cycle.

These losses vary considerably from cycle to cycle. It is so, basically, because, as the examination of this effect has shown, in the robot a compression spring is used, which loses its stability and contacts with guide rail in deformed state. It gives in appearance of frictional force between the spring and the guide. Besides, the internal losses of energy are big enough during the process of loading - unloading of the spring.

To decrease power losses during robot's movement, the design of the robot was then slightly changed (Fig. 6). Instead of one compression spring of squeezing, four extension springs were used (keeping the same total rigidity 900 n/m with a smaller diameter of a spring wire). This allowed to save up to 75 percents of energy accumulated in a spring and, principally, eliminated completely the instability of power loss quantity.

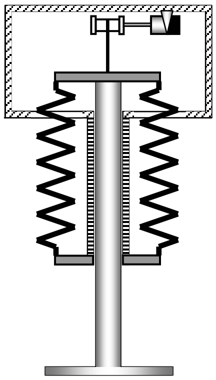

Fig. 6. Kinematic configuration of the hopping robot with extension spring.

During experiments the condition $T_C < T_F$ was always satisfied. The experiments have shown, that in spite of a simplicity of the control system, the robot holds stable height of jumps with deviations from the given value not exceeding 0,3 %. It is also shown experimentally, that at presence of disturbing effects the robot changes height of jump, but returns to a specified height of jumps after several cycles (Fig. 7).

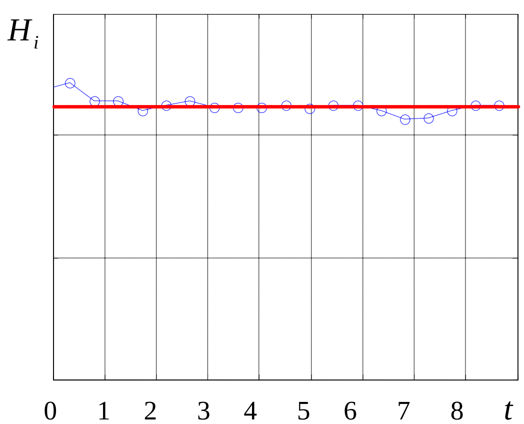

Fig. 7. Experimental values of height of jumps vs. time. Disturbance with positive energy acted at the moment *t=0*, disturbance with negative energy acted at the moment *t=6* s. Blue circles: real height of jumps; red line: given height of jumps. Similar results were obtained by means of calculations using equations (2, 4, 5, 6, 8).

Let us notice that during experiments two variants of starting of robot work were considered. In the first case, the robot was lifted on a height H, corresponded to a given regime of work, then the spring was contracted on the corresponding magnitude l and then the robot was released. In the second case, the robot was not lifted, the spring was contracted on the magnitude somewhat exceeding a magnitude $l + S$, then the drive was reversed with the maximal possible velocity.

For additional decrease of energy consumption, a special dual drive with changeable transmission ratio has been designed, which allowed a decrease of energy expenses at the cost of the increase of motor efficiency.

VI. Conclusion

A hopping resonance robot has been studied with a compensation of energy losses during robot's flight. On the base of dynamic calculations, new dynamic effects are revealed that are connected with the movement stability of the hopping robot. It was shown that, on the one hand, the considered robot makes it possible to use a low-power motor; on the other hand, under certain conditions, such robot possesses self-properties providing a natural stabilization of the given regime of work. It is shown that if the conditions of natural stabilization do not fulfill, the proposed control algorithm allows a stabilization of the motion even at the presence of significant disturbances. The results obtained are confirmed by calculations and experimentally.

It is planned to make a quadruped running resonance robot, with each leg designed on the base of the principles described in the present paper.

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