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Dual Drive for Vertical Movement of Resonance Hopping Robot

In the present study vertical movements of resonance hopping robot of special construction with one leg and dual drive are considered. The construction of hopping robot with compensation of losses during flight of the robot allows employing a simple control system and having a stable regime of its operation so that the robot has self-property to maintain a specified height of jumping. The data on dynamical calculation, simulations and experimental testing are discussed. The solution of the problem of actuator's optimum parameters choice (including variable transmission ratio) for the considered robot is presented.

Introduction

Normally, hopping robots with electric motors have elastic devices for saving of 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 [1-5]. When the contact is switched off, the drive motor cuts off. Using such control it is necessary to utilize a relatively powerful (and consequently, rather heavy) electromotor, which is capable to make a compensation of losses during a very short time of the contact of robot's leg with a bearing surface.

Considering that the time of the contact is nearly five-ten times less than a complete cycle time, it seems to be advantageous to make a compensation of losses during robot's flight time instead of during the time of the contact of robot's leg with bearing surface [6-8]. This approach let us to use a motor of a considerably low power, that results in significant decrease of robot's weight and thus a consumption of energy is diminished.

It is also possible to decrease energy consumption minimizing 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 always give satisfactory results. For example, in the paper [9] it is shown that in some cases the capacity factor of energy of a compressed spring could constitute only 20 %.

Another problem related to 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 [10]. If this is the case, a provision of a stable operation of the robot is usually accomplished at the expense of rather complicate control system.

It is shown [7] that under certain conditions, hopping robot can maintain self-stabilization without any sensor. However, in this work a considered robot model was very simplified (a negligibly small mass of leg, ideal spring).

The aim of the work is to elaborate a special construction of hopping robot [8], [11] with compensation of losses during flight of the robot. This robot has been designed in CAR UPM-CSIC (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 paper energy losses inside spring are considered as well as shock interactions of robot's leg with its body and bearing surface.

The Robot Operation

A kinematic configuration of the robot is shown in Fig. 1. The robot has a body, in which a leg with a mechanical stop block is anchored to be able to make forward movements.

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 contains a sensor of rotational displacement of a motor and a sensor of a contact of the leg and the bearing surface.

The drive motor makes a cylinder (joint with the robot) turn through some angle during robot's flight. 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 before 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.

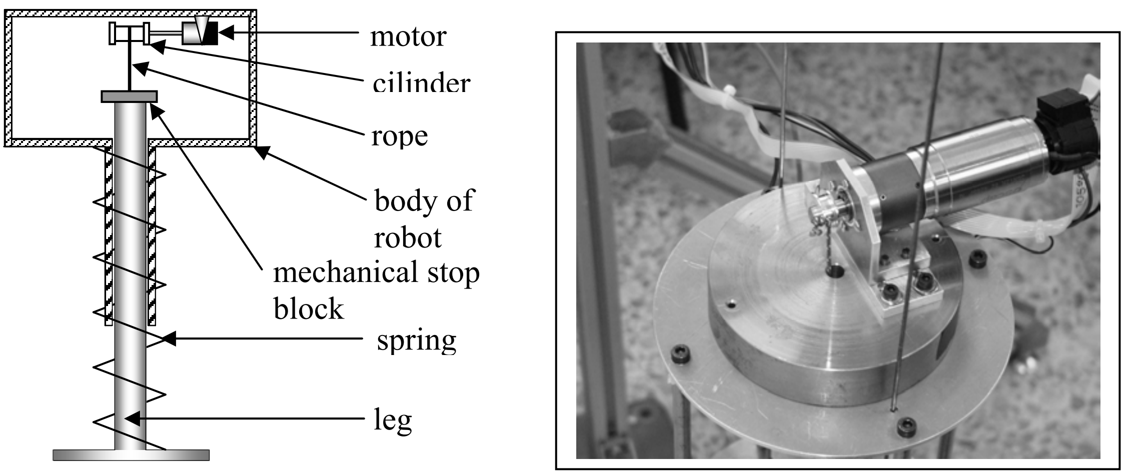


Figure 1 – Hopping robot with a compression spring

When robot's leg and bearing surface contact, the leg stops. The robot's body, having certain velocity, continues moving downwards deforming the spring additionally. The body of the robot being at 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. Then the whole process repeats. The obvious condition of a stable operation of the robot is:

$$H_{i+1} = H_i \,. \qquad (1)$$

To fulfil 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.

The mode of functioning of the control algorithm is shown on Fig. 2. The upper curve corresponds to the state of the sensor of a contact of the leg with the bearing surface; the lower curve corresponds to the angular position of the cylinder.

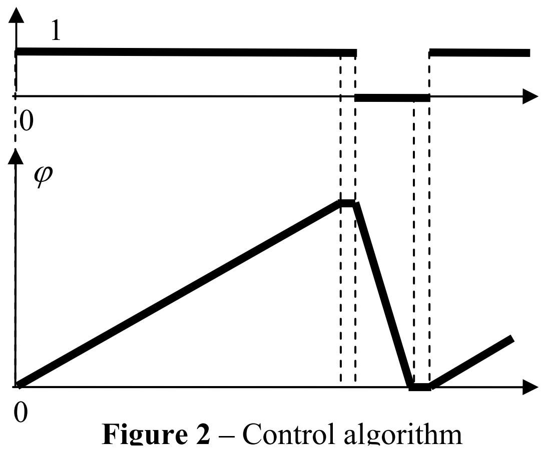


Figure 2 – Control algorithm

Dynamical Equations

The robot's movement equations are based on a progressive use of corresponding laws of conservation for each stage of movement including impacts between the leg and the body of the robot (Fig. 3).

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 half of a mass of resilient element.

On the base of a mechanical energy conservation law [for the robot movement from initial position (Fig. 3a) into a position immediately before the impact of the leg of the robot against bearing surface (Fig. 2b)]:

$$V_{1i} = \sqrt{2gH_i}\,, \qquad (2)$$

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

On Fig. 3b, 3c the process is represented of the impact of the robot's leg against bearing surface (3b – a position immediately before the impact, 3c – 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. On Fig. 3c, 3d 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:

$$MgS_i + \frac{MV_{1i}^2 + c_1 l^2}{2} = \frac{c_1(S_i + l)^2}{2}, \tag{3}$$

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

On Fig. 3d, 3e 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:

$$\frac{c_2(S_i + l)^2}{2} = \frac{MV_{2i}^2}{2} + Mg(S_i + l), \tag{4}$$

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. 3e, 3f the process of impact is shown of a stop block of a leg against the robot's body (3e – a position immediately before impact, 3f – 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:

$$MV_{2i} = (M + m)V_{3i}. \tag{5}$$

On Fig. 3f, 3g the last stage of a movement cycle of the robot is shown. For this movement, on the base of the mechanical energy conservation law, we have:

$$\frac{V_{3i}^2}{2} + gl = gH_{i+1}. \tag{6}$$

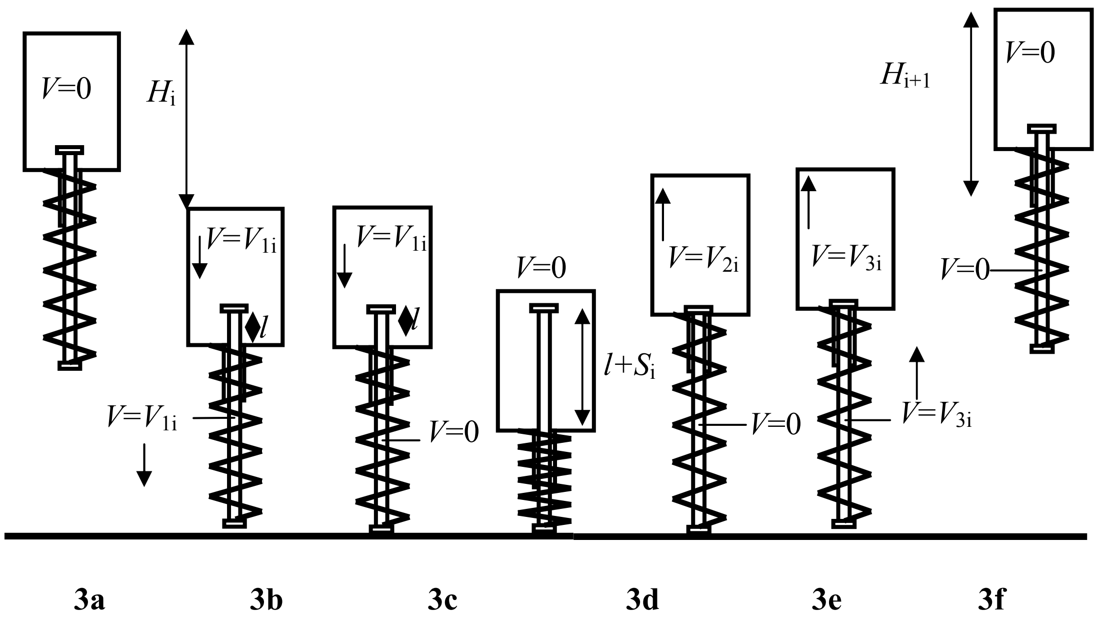


Figure 3 – Movement's cycle

It has been shown [11] that the movement of the robot described by the system of the equations (1) – (6) is stable.

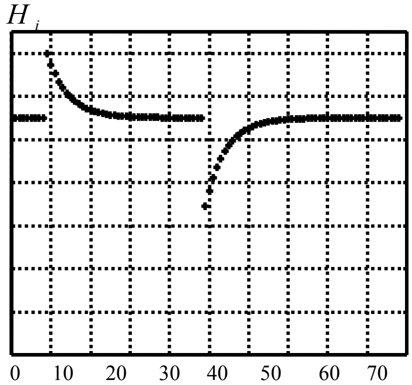


Figure 4 – Height of jump vs. number of jump

Thus, a dependence of values of height of jumps vs. number of jumps (simulation) is shown on Fig. 4. Jumps 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 the system is working with reserve of stability.

Preliminary Experiments

According to the scheme presented on Fig. 1, a laboratory prototype of a hopping robot was designed, manufactured and tested to verify experimentally the obtained results. The prototype is designed that can jump up to 0,4 m, has a weight 3,5 kg and the weight of its leg is 0,15 kg [11]. Preliminary 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.

The mentioned losses vary considerably from cycle to cycle because, as the examination of this effect has shown, in the robot a compression spring is used, which looses its stability and contacts with guide rail being in deformed state. This causes appearance of force of friction between the spring and the guide. Besides, the internal losses of energy are significant during the process of loading – unloading of the spring.

To decrease power loss during robot's movement, the robot's design has been changed (Fig. 5). One compression spring of squeezing was replaced by four extension springs (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, to eliminate completely the instability of power loss quantity.

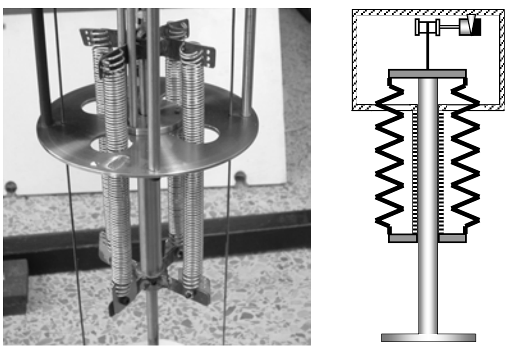


Figure 5 – Robot with extension spring

It has been shown experimentally, in spite of a simplicity of the control system, the robot holds stable height of jumps with small deviations from the given value. It is also demonstrated that at presence of disturbing effects the robot changes height of jump but returns to a specified height of jumps after several cycles (Fig. 6).

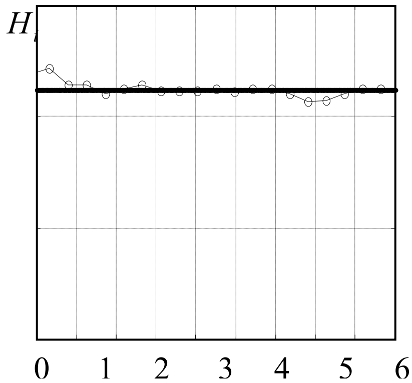


Figure 6 – Experimental values of height of jumps vs. time. Curve with circles – real height of jumps; solid line – given height of jumps.

Disturbance with positive energy acted at the moment $t = 0$, disturbance with negative energy acted at the moment $t = 6$ s. Movement is stable.

Dual Drive

As has been shown above, the robot's motion is stable when drive's movement finishes before the end of the corresponding phase of the robot's movement, the law of movement of spring being not important from the point of view of stability of jumps' height. It should to be mentioned that in the described system the drive does not work optimally because it performs two principally different modes of movements. During the process of stretching of the spring (a working stroke), the motor should turn the cylinder a certain angle relatively slow. During this movement, the external load upon the motor increases and reaches its maximum at the end position, when the motor holds the cylinder. The reverse movement of the motor (the same angle turn – an idle stroke) takes place without any external load but should occur several times as fast. This leads to discrepant requirements while choosing a transmission ratio of the reducer.

The employment of the drive with the changeable characteristics (dual drive) allows eliminating this discrepancy. One of the alternative designs of the dual drives is shown in Fig. 7. The design of this drive is based on the use of a cam mechanism.

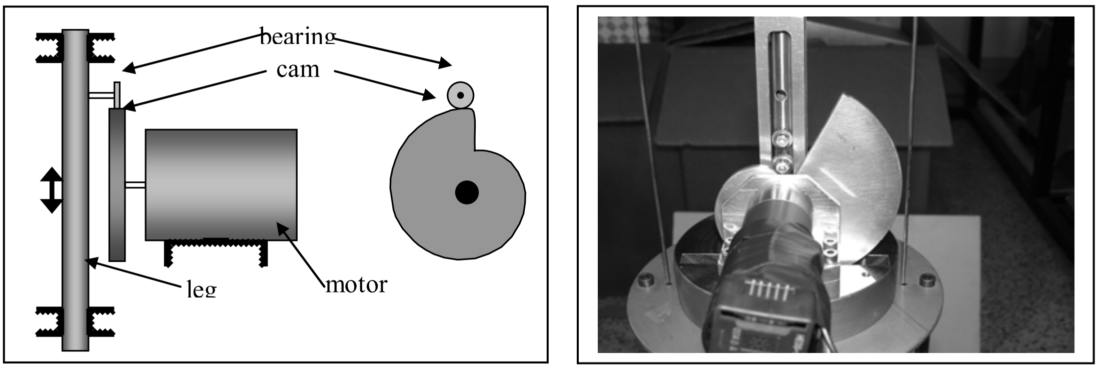


Figure 7 – Dual drive

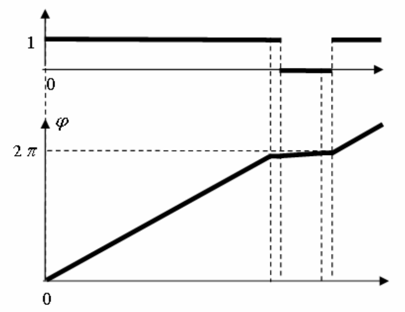


Figure 8 – Control algorithm for dual drive

The cam mechanism is fitted to the shaft of the motor-reducer, and interacts with the robot's leg through a bearing fixed on the leg. In contrast to the control algorithm shown on Fig. 2, a working stroke is characterized, when employing this cam mechanism, by a considerably bigger angle of a motor turn than an idle stroke does (Fig. 8), which allows to overcome the discrepancy on choosing a transmission ratio of the reducer.

The use of the drive with a changeable transmission ratio allowed to solve another problem associated with the increase in the motor effectiveness. It is known [12] that the highest effectiveness of the electromotor is achieved while it is turning around with the constant speed at constant external load. In the process of the performing of the working stroke, there occurs a resilient members' deformation, which is characterized by a change of force of elasticity. However, choosing a special design of a working part of the cam, we can get a constant torque on the axis of the motor that deforms resilient members through this cam.

The shape of the working part of the cam can be written in polar coordinates as:

$$\rho = \rho_0 + f(\varphi), \tag{7}$$

where φ – an angle of the cam's turn, ρ – radius, f – unknown function.

As has been shown above, the best effectiveness of the electromotor is achieved while it is moving with the constant speed at the constant load. In this case the cam has also a constant speed ω, that can be calculated by the formula:

$$\omega = \frac{d\varphi}{dt}. \tag{8}$$

The energy of the resilient elements is calculated by the formula:

$$E = c_1 \frac{(\rho - \rho_0)^2}{2}. \tag{9}$$

Disregarding friction and inertia forces in comparison with the force of resilient elements, we obtain that at motor working with a constant speed and a constant load, the motor power will be constant also, and can be calculated by the formula:

$$P = \frac{dE}{dt} = Const. \tag{10}$$

From the equations (7) – (10), after separation of variables and integration, we find an unknown function $f(\varphi)$. Substituting the found function in (7) we find the equation, which describes the optimal shape of the working surface of a cam:

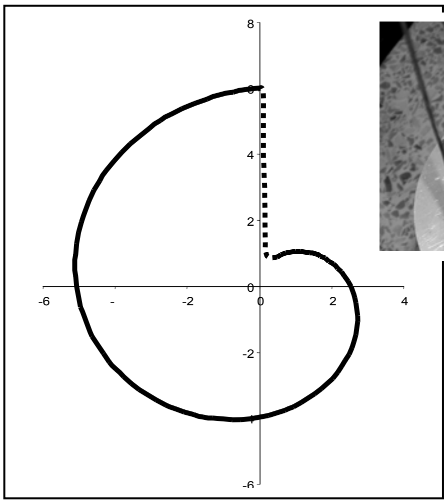
$$\rho = \rho_0 + \sqrt{\frac{2P\varphi}{c_1\omega} + B}, \tag{11}$$

where a magnitude of the cam's radius in the beginning of the working zone ρ_0 is determined from constructional features. An integration constant B is calculated from the condition that the cam's radius in the end of the cam's working zone meets a relation:

$$\rho_1 - \rho_0 = l\,. \tag{12}$$

As an example, on Fig. 9 there is shown an optimal cam' shape for the case when the cam's working zone is situated in the range from $\varphi = \frac{\pi}{6}$ to $\varphi = 2\pi$, $\rho_0 = 1$ cm, $\rho_1 = 6$ cm. The general view of the resonance hopping robot with a dual drive is presented on Fig. 10.

It was mentioned above that to ensure a stability margin, the working movement of a cam, while it realizes a tension of springs, should terminate before the flight time is completed. In this case with the help of a motor it is necessary to retain springs stretched during certain time (Fig. 2, 8 – the first horizontal section of the plot)/ In this regime the electric motor consumes a considerable amount of energy, which leads only to a motor overheating and is not utilized in any way by a robot (efficiency of a motor in this case is null). It is more: the bigger is the time, during which the motor retains springs stretched, the bigger is a stability margin of a movement. To eliminate these non-rational energy expenses, saving a possibility of creation of a stability margin, a special small hollow was made at the end of a working area of a cam (Fig. 7). This hollow plays a role of a lock. At the moment, when a bearing, which is anchored on a leg, falls in this hollow, an equilibrium position of the leg, which is under the action of stretched springs, becomes stable. In this case the electric motor should not apply the torque to maintain springs in the stretched state (a motor can be turned off). Additional positive effect, which offers this lock, is connected with the fact that before each robot jump, springs are necessarily stretched on the very same length with an accuracy, defined by an accuracy of mechanical contact of the bearing and hollow. This fact is very important, because the magnitude of stretching of springs influences directly



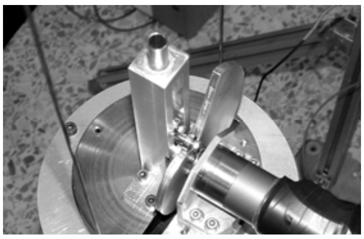


Figure 9 – The optimal shape of the working part of the cam (solid line)

Experiments with Dual Drive

During experiments the parameters of a drive were selected (Fig. 9), which provided some stability margin of movement. Under such conditions, both the disturbances with positive energy, and the disturbances with negative energy were compensated by a drive during several cycles. On figure 10 a typical curve is presented of dependence of flight time on the number of jumps for a situation, when the disturbing effect with negative energy operates at the initial moment.

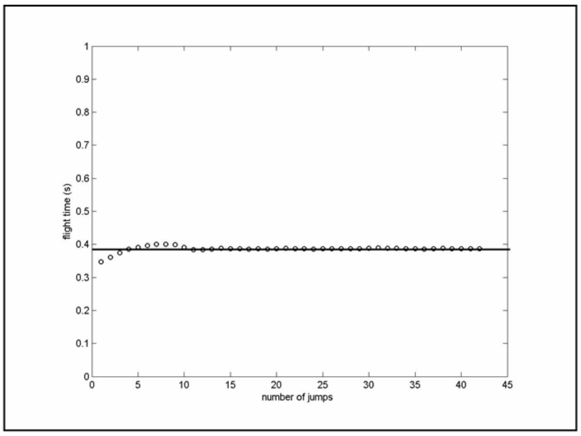


Figure 10 – Flight time vs. the number of jumps. Curve with circles – experimental height of jumps; solid line – given height of jumps. Mass of robot is 4.2 kg, mass of leg is 0,25 kg., c = 1000 N/m

It is obvious that after a few jumps a deficiency of energy that a robot had at the initial moment is compensated with the help of electric motor. After the compensation the flight time of the robot during next jumps remains practically constant. The constant height of jumps after disturbing effect action confirms a presence of the effect of self-stabilization, which had been shown at simulation and during preliminary experiments. Jumping robot behaves similarly at presence of disturbing effect with positive energy.

In steady-stated regime, robot'speed at the moment of separation from a surface is 1,8 m/s, and at the moment before a shock against surface – 2,1 m/s. Mechanical power transmitted from a motor is 3.2 W. Thus, in one cycle robot gains for compensation of energy losses 1,25 J, and the total robot's mechanical energy during robot's movement makes 4,45 J.

The described experiments were performed under conditions when a base on which robot's leg rested, was fixed and the shock of a leg against this base could be considered absolutely inelastic. Even under these conditions the known effect of emerging of noise manifests itself at the moment of a change state of sensor of contact of leg and surface (as a sensor a simple contact limit switch was utilized). The time during which this noise existed was very small (less than 0.01 s). To eliminate negative consequences of this effect a control system stopped the information reading from this sensor during indicated period of time.

To define the limits of possible application of a proposed simplest control system, additional experiments were performed. In these experiments an elastic beam fixed at its end points, served as a bearing surface. At the centre of this beam a body was fixed on which a leg of the robot rested. To modify a frequency of self oscillations of the beam a mass of the fixed body was being changed. The experiments have shown that if a frequency of self oscillations of a beam is big enough, a control system provides a stable height of jumps of the robot. Let us notice that in these conditions the time during which false signals of a sensor take place can increase two – three times. This deficiency is easily compensated with the help of increase of a time during which a control system would not read a signal from this sensor.

If the self frequency of oscillations of a beam is commensurable with the frequency of jumps of the robot the situation changes drastically. In such situation the employed simplest control system cannot provide a stable height of jumps of the robot. In this case to stabilize the height of jumps it is necessary to utilize more complicate control system.

Conclusions

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. 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. The results obtained are confirmed by calculations and experimentally.

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Привод с изменяемыми свойствами для вертикального движения резонансного прыгающего робота

В настоящей работе рассматриваются вертикальные движения резонансного прыгающего робота специальной конструкции с одной ногой и приводом с изменяемыми свойствами. Конструкция робота предусматривает, что компенсация потерь энергии производится в фазе полета. Это дает возможность использовать простую систему управления и позволяет стабилизировать рабочий режим за счет того, что робот имеет естественную самостабилизацию заданной высоты прыжков. Обсуждаются результаты расчетов, моделирования и экспериментов. Для рассматриваемого робота представлено решение задачи выбора оптимальных параметров, включая параметры привода с изменяемыми свойствами.

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