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AUTOMATED WEIGHT COMPENSATION SYSTEM FOR GROUND-BASED TRYOUT OF SPACE VEHICLE SOLAR PANELS

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In the process of ground-based tryout of solar panels placed aboard the spacecraft there appears the problem of gravity effect compensation. The energy of deployment mechanism is extremely limited, the weight and strength of the structure being calculated for weightlessness conditions. Therefore, under the force of gravity, the power of deployment drives may not be enough to complete the tryout, and the structure itself may be destroyed. Taking into account these difficulties, specialized stands the main part of which is the so-called weight compensation system are designed and created to conduct ground-based pilot tryout. Active weight compensation systems are most effective in this case.

In the stands with active weight compensation systems all forces generated by the stand and movements of the stand parts occur through controlled drives. By introducing various sensors into the weight compensation system and by the use of their signals for generation of controlling actions in the control system it becomes possible to significantly increase the level of gravity effect compensation, as well as to minimize the influence of the stand parts inertia.

The paper presents the results of the designing, building and testing of the automated active weight compensation system for solar panels. The system provides weight compensation when conducting ground-based experimental tryout of any objects (solar panels, rods, multi-tier spokes, etc.) having a long and transformable in one direction form for distances of the order of 20 m (longitudinal direction). This system also provides movement of the pieces of a tested object in the transverse direction and in height for distances of up to 5 m.

The results of departmental tests showed that the weight compensation system with specified parameters described in this paper allows for ground-based tryout of the deployment of solar panels of all constructions, both currently existing and being developed for the future.

Keywords: solar panel, spacecraft, active weight compensation system, efficiency of the weight compensation system.

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АВТОМАТИЗИРОВАННАЯ СИСТЕМА ОБЕЗВЕШИВАНИЯ ДЛЯ НАЗЕМНОЙ ОТРАБОТКИ СОЛНЕЧНЫХ БАТАРЕЙ КОСМИЧЕСКИХ АППАРАТОВ

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В процессе наземной отработки солнечных батарей, размещаемых на борту космических аппаратов, возникает проблема компенсации влияния силы тяжести. Энергетика механизма раскрытия чрезвычайно ограничена, а вес и прочность конструкции рассчитываются на условия невесомости. Поэтому в условиях действия силы тяжести мощности приводов раскрытия может не хватить для полноценной отработки, а сама конструкция, как крайний случай, может быть разрушена. Учитывая данные сложности, для проведения наземной экспериментальной отработки разрабатываются и создаются специализированные стенды, основной частью которых являются так называемые системы обезвешивания. Наиболее эффективными в данном случае являются активные системы обезвешивания.

В стендах с активными системами обезвешивания все силы, генерируемые в стенде, и перемещения составных частей стенда происходят за счет управляемых приводов. Путем введения в конструкцию системы обезвешивания различных датчиков и использования их сигналов для выработки управляющих воздействий в системе управления удается значительно повысить степень компенсации влияния силы тяжести, а также минимизировать влияние инерционности частей стенда.

Представлены результаты разработки, создания и испытаний автоматизированной активной системы, предназначенной для обезвешивания солнечных батарей. Созданная система обеспечивает обезвешивание при проведении наземной экспериментальной отработки любых объектов (солнечных батарей, штанг, многозвенных спиц и т. д.), имеющих протяженную и трансформируемую в одном направлении форму на расстояния порядка 20 м (продольное направление). Также данная система обеспечивает перемещение частей тестируемого изделия в поперечном направлении и по высоте на расстояния до 5 м.

Результаты ведомственных испытаний показали, что описанная система обезвешивания с указанными параметрами позволяет производить наземную отработку раскрытия солнечных батарей всех конструкций, как существующих в настоящее время, так и разрабатываемых на перспективу.

Ключевые слова: солнечная батарея, космический аппарат, активная система обезвешивания, эффективность системы обезвешивания.

Introduction. At present, in the process of space vehicles (SV) development one of the most important tasks is to increase their reliability and elongate their service life during the flight. The solution of this problem is impossible without comprehensive ground-based experimental testing (GET) of both the SV as a whole and its component parts. The greatest difficulties arise with GET of so-called large-scale transformable systems (LTS). LTS include: antenna-reflectors, solar panels (SP), various retractable rods, etc. The complexity of GET of such objects is due to their considerable size (often the linear dimensions of these objects exceed the dimensions of the SV tens of times), the energy of the mechanism of deployment (transformation) is extremely limited, the weight and strength of the structure being calculated for conditions of weightlessness. Therefore, under the action of gravity, the power of the deployment drives may not be enough for an adequate tryout, and the structure itself can be destroyed. Taking into account these difficulties, specialized stands the main part of which is the so called weight compensation system (WCS) [1–8] are being designed and created for carrying out GET.

The general idea of weight compensation is that special constructions compensate for the gravity forces acting on each of the non-transformable parts, and also compensate the moments created by the action of gravity on each such part. This can be achieved by applying to the center of mass of each non-transformable part a force equal to the weight of this part and directed strictly upward. But such a "trivial" solution does not always turn out to be constructively realizable. In general, the stand should provide a three-dimensional movement of parts of an object to be weight-compensated in an arbitrary direction, but often the features of the topology of the object being transformed are used to simplify the design of the stand, so either symmetry axes or selected directions appear [2].

When developing a WCS, the following main tasks are solved:

– choice of the method of compensation for gravity acting on the objects to be weight-compensated;

– ensuring the movement of the points of suspension of the object to be weight-compensated in space along the necessary trajectories;

– ensuring the independence of the weight-compensating forces during the movement of the suspension point;

– minimization or complete elimination of the inertia effect of the parts of the WCS on the operation of the mechanisms of a tested product.

In addition, some other tasks can be solved simultaneously: minimization of bending and other types of deformation of product designs, minimization of change in friction forces in hinges, etc.

Weight compensation systems can be divided into three types according to the way of solving the main tasks mentioned above:

– systems with a passive type of weight compensation [2; 3];

– systems with an active type of weight compensation [4];

– systems with an active-passive type of weight compensation [7; 8].

In systems of the first type, the parts of the product to be weight-compensated and the stand move under the action of movements and forces which are formed due to the energy of the product drives, the balance weights and the spring elements of the stand. The main disadvantage of such systems is the sharp complication of their design when the size of LTS increases and the practical impossibility of minimizing the effect of inertial properties of WCS on the operation of a tested product. As a rule, these systems are highly specialized and are intended for GET of the final set of products. Due to these shortcomings, the scope of application of such systems is limited to GET of relatively simple objects consisting of 2–3 elements and with relatively non-rigid requirements for compensation of gravity (usually, in statics, the error of compensation is several percent).

In stands with active systems of weight compensation all the forces generated in the stand and the movements of the component parts of the stand are due to controlled drives. In this case, by introducing various sensors into the design of the WCS and using their signals to generate controlling actions in the control system it is possible to significantly increase the degree of compensation for the effect of gravity, and also to minimize the influence of the inertia of the stand parts [9]. Structurally, such a system becomes much simpler. The disadvantages of these systems are the complexity of the control algorithms, large labor costs for their development and high probability of self-oscillations.

In systems with an active-passive type of weight compensation, there are in some cases advantages and disadvantages of the systems of the first two types and the scope of their application, as that of passive systems, is limited.

Formulation of the problem. The purpose of this work was the development of an automated active weight compensation system for the deployment of extended products [10]. Weight compensation of a product can be provided only in two ways: the first one is hanging on suspenders with a movable suspension point and using mobile supports (an exotic case of immersion in a pool with dense liquid is not considered). In our case WCS with the use of a suspension system is structurally more convenient. This WCS must ensure weight compensation during GET of any objects (solar batteries, rods, multi-link spokes, etc.) having an extended and transformable in one direction form for distances of the order of 20 m (longitudinal direction). Also, this system should allow the parts of the tested product to be moved in the transverse direction and in height for distances up to 5 m [11]. Concrete specifications are given in table.

An important issue in conducting GET is the question of energy losses of the drives of a tested product deployment while overcoming the "parasitic" forces, which are the resistance forces in the WCS and an uncompensated part of the gravity force. These losses are due to the imperfection of the WCS design and the "non-ideal" operation of feedback and sensors in this system. A full account of all the differences in the ground-based experiment and the conditions of an orbital flight is hardly possible, and therefore a certain compromise solution was adopted on the methodology for determining losses, namely:

1. In each relatively short period of time (of the order of 0.1 seconds) it is considered that the instantaneous value of the speed of the part to be weight-compensated, its acceleration, the deviation from the vertical of the suspender on which this product is suspended are considered constant (i. e., the values of all "parasitic" forces which must be overcome by the deployment mechanism during the process of deployment are constant).

2. "Parasitic" work of the deployment system on this section – $A\text{п}_i$ is given by the expression:

$$A\text{п}_i = Fz_i \cdot \delta z_i + Fy_i \cdot \delta y_i + Fx_i \cdot \delta x_i,$$

where Fz_i, Fy_i, Fx_i are the values of the "parasitic forces" acting at i time moment on the weight-compensated part along the corresponding directions; δz_i, δy_i, δx_i are the values of the displacements for the same moment of time. In this case, only those coordinates are taken into account, in the direction of which the forces of the deployment system act. Forces perpendicular to those created by the deployment drives create additional frictional forces in the hinges, which certainly need to be reduced, but the direct calculation of their effect on the losses is extremely complicated.

3. The total energy losses of the deployment drives for the extension of this part – $A\text{п}$ – are calculated as the sum of the "parasitic" works along the entire path of deployment of the part to be weight-compensated:

$$A\text{п} = \sum_{i=0}^{N} A\text{п}_i ,$$

where N is the number of sections for the entire time of product deployment.

The total energy losses of the deployment drives are the sum of parasitic work moving each "non-transformable" part of the product to be weight-compensated.

Technical characteristics of WCS

№	Parameter name	Index
1	Number of independently weight-compensated parts (pieces), of which:	12
2	with mass up to 80 kg	3
3	with mass up to 35 kg	6
4	with mass up to 10 kg	3
5	Maximum speed of the parts to be weight-compensated, m/s: longitudinal transverse vertical	 1 1 0.4
6	Maximum acceleration of the parts to be weight-compensated, m/s^2: longitudinal transverse vertical	 0.5 0.5 0.2
7	Maximum travel of parts of the article to be weight-compensated, m: longitudinal transverse vertical	 17 ±2 ±2.5
8	Energy losses of the drives of the tested product deployment system to overcome resistance in WCS and gravity,%, not more than	10

The stand and WCS construction. Due to the fact that the parts of tested products travel the distance of tens of meters (*X* coordinate) in one direction and are limited to the distance of a few meters in the other direction (*Y* – transverse, *Z* – vertical), the portal structure was taken as a basis. The portal was moved along the two guides with a toothed belt along *X* coordinate, the carriage was moved along the portal in the transverse direction and this carriage, in its turn, ensured the vertical moving of the object to be weight-compensated [12; 13]. The movement of the portal was due to the engagement of the gears of the portal support assemblies with the toothed belt. The drives that move around each coordinate were independent. The considerations for choosing the drives and the control system for their displacements were similar to those given in [14]. The error in compensation of the weight component was measured with the help of weight sensors, the data from which were transmitted to the control system via the radio channel. In *X* and *Y* axes, the delay signal (or the lead signal) of the portal and the carriage was the deviation of the suspension cable from the vertical. Directional *X* coordinates were located in 3 tiers (on each tier there were 3 portals). Particular attention was paid to the speed of the control system and the sensors of mismatch. The data acquisition period from all sensors and the control cycle time were 30 ms. Mitsubishi Electric equipment was adopted as an automation platform [15]. The exterior view of the portal with the carriage and WCS assembly is shown in fig. 1, *a*, *b*, respectively.

The WCS operation was tested during the weight compensation of a solar battery consisting of 3 panels and a frame (fig. 2). The objective function of the control system for the WCS drives was to minimize the deviations of suspension cables from the vertical and the deviation of the tension of the suspender cables from the set values. Because there was no motion of the SP in the vertical direction (it arose only because of inadequate parallel alignment of the SP deployment direction and the WCS guides, and out-of-parallelism of the axes of the individual panels), the tests of WCS in the vertical direction were not fully carried out. In the operation of the WCS control system, the PID control algorithm was used [16; 17].

Experimental results and discussion of the obtained temporal dependencies during the deployment. During the experiments, the PID regulator coefficients (gain factors in the WCS feedback loop) were selected from the condition of the absence of electromechanical resonances for various designs of the products being inspected and the conditions for their deployment. This condition was dictated by the strict requirement of mechanical safety of the product to be weight-compensated. Thus, a certain "safe" range of values of the PID regulator coefficients was determined. It was in this range of coefficients that experiments were carried out. After carrying out the experiments and processing their results, the following dependencies were obtained for each of the parts to be weight-compensated:

– the speed of movement of a given part along *X* axis as a function of time;

– speed of movement of a given part along *Y* axis as a function of time;

– the dependence of the parasitic energy losses of the SP deployment mechanisms when moving the panels along each of the coordinates.

Moving of an intermediate panel (it has the largest weight and a significant travel range) and the tip panel – it has the maximum displacement along *X* axis – is the most interesting. The movement of all the panels along *Y* axis practically did not affect the energy losses due to the small range of displacements. The dependencies obtained on the graphs are similar for each of the parts to be weight-compensated (they differ only in numerical values), so below in fig. 3–8 only the results for the tip panel are shown.

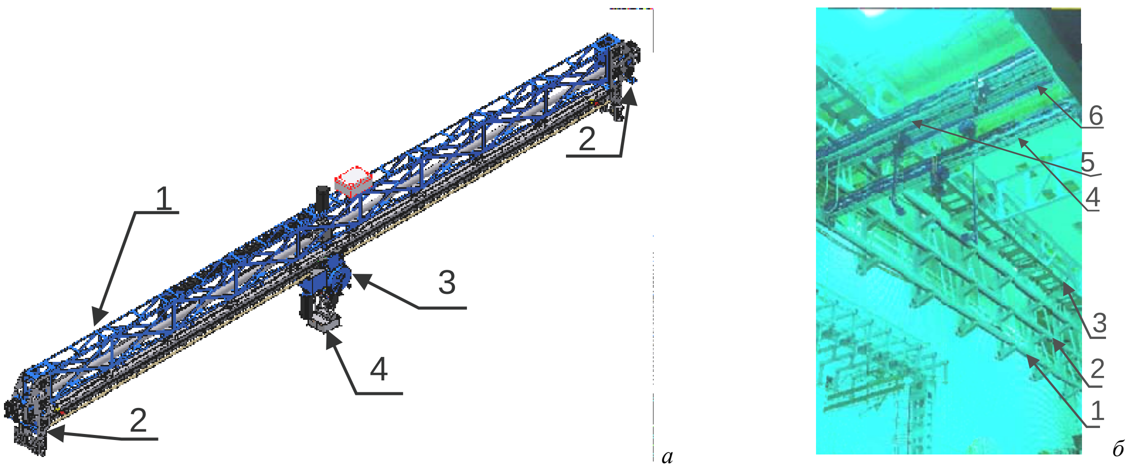

Fig. 1. WCS portal (*a*): *1* – portal body; *2* – support assembly; *3* – carriage; *4* – vertical displacement node with error sensors in *X* and *Y* coordinates; WCS in assembly (*b*): *1*, *2*, *3* – left guides (3 tiers); *4*, *5*, *6* – portals of three tiers

Рис. 1. Портал СО (*а*): *1* – корпус портала; *2* – опорный узел; *3* – каретка; *4* – узел вертикального перемещения с датчиками рассогласования по координатам *X* и *Y*; СО в сборе (*б*): *1*, *2*, *3* – левые направляющие (3 яруса); *4*, *5*, *6* – порталы трех ярусов

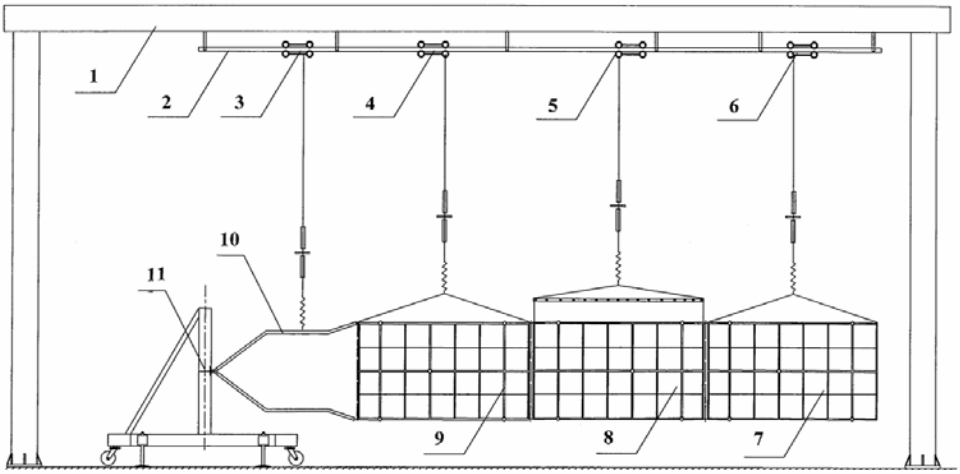

Fig. 2. Schematic representation of the deployed solar panel used in WCS tests:
1 – load-bearing column; *2* – double guides; *3* – carriage with a suspender of a rod weight compensation; *4* – carriage with a suspender of an inboard panel weight compensation; *5* – carriage with a suspender of an intermediate package weight compensation; *6* – carriage with a suspender of a tip panel weight compensation; *7* – tip panel; *8* – intermediate panel; *9* – inboard panel; *10* – frame; *11* – IR satellite frame

Рис. 2. Схематичное изображение раскрытой солнечной батареи, используемой при испытаниях СО:
1 – силовая колонна; *2* – двойные направляющие; *3* – каретка с вывеской обезвешивания штанги; *4* – каретка с вывеской обезвешивания корневой панели; *5* – каретка с вывеской обезвешивания промежуточного пакета; *6* – каретка с вывеской обезвешивания концевой панели; *7* – концевая панель; *8* – промежуточная панель; *9* – корневая панель; *10* – рама; *11* – рама ИК спутника

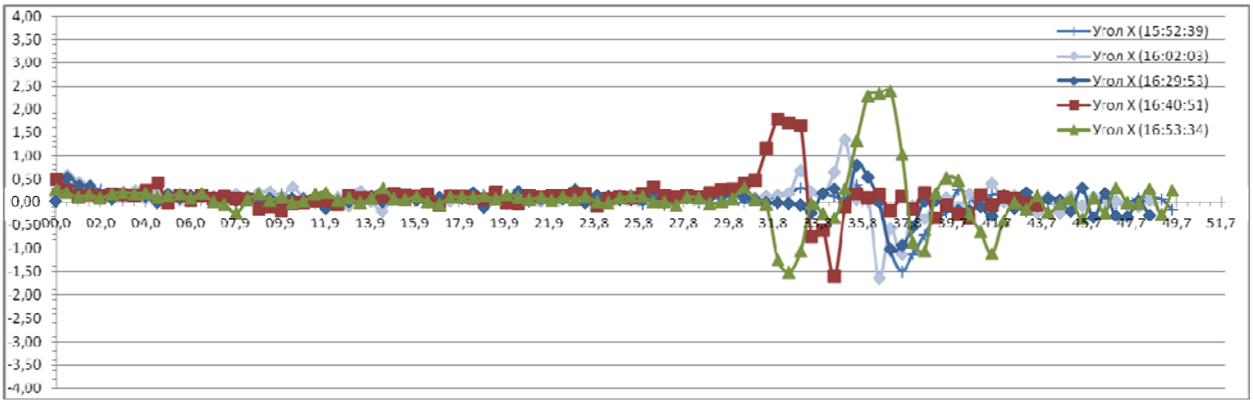

Fig. 3. Time dependence of the deviation angle of the tip panel suspender from the vertical in the direction of *X* axis (time is given in seconds, deviation – in degrees)

Рис. 3. Временная зависимость угла отклонения вывески концевой панели от вертикали в направлении оси *X* (время – в секундах, отклонение – в градусах)

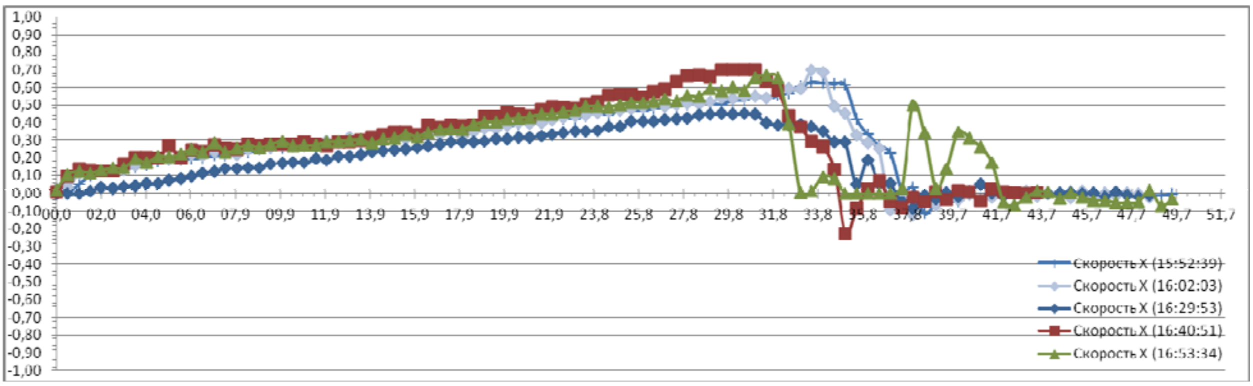

Fig. 4. Time dependence of the tip panel velocity in *X* direction

Рис. 4. Временная зависимость скорости движения концевой панели в направлении *X*

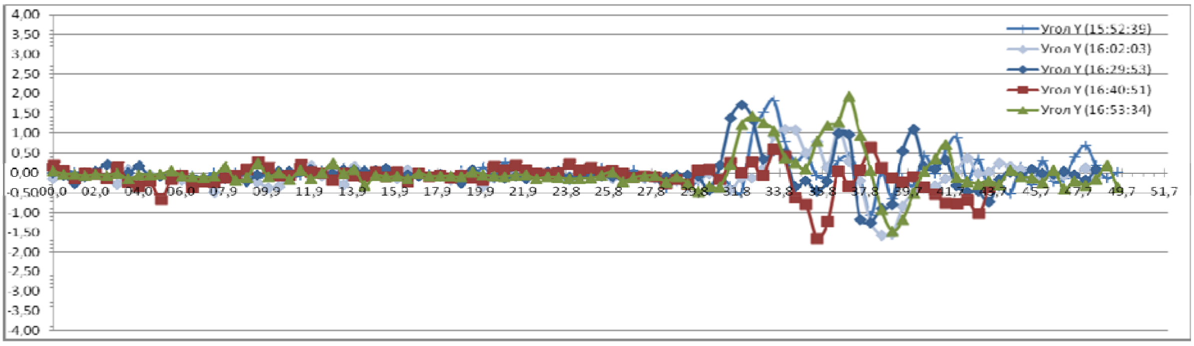

Fig. 5. Time dependence of the deviation angle of the tip panel suspender from the vertical in the direction of *Y* axis

Рис. 5. Временная зависимость угла отклонения вывески концевой панели от вертикали в направлении оси *Y*

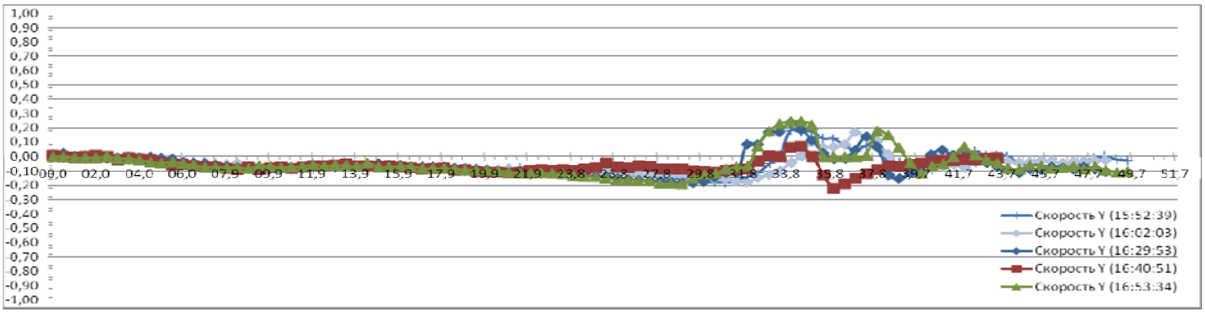

Fig. 6. Time dependence of the tip panel velocity in *Y* direction

Рис. 6. Временная зависимость скорости движения концевой панели в направлении *Y*

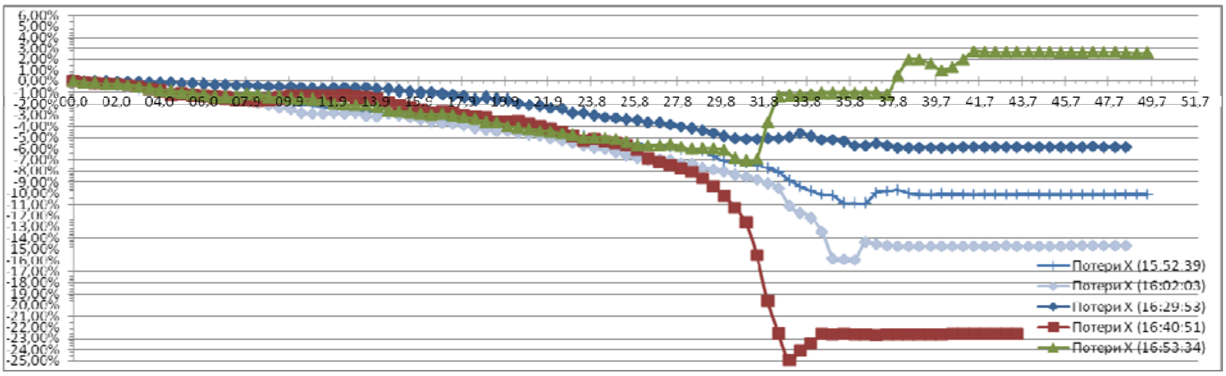

Fig. 7. Time dependence of the “parasitic” energy losses of the mechanism of opening the end panel (% of the energy stored in the mechanism) when moving in the *X* direction

Рис. 7. Временная зависимость «паразитных» потерь энергии механизма раскрытия концевой панели (% от энергии, запасенной в механизме) при движении в направлении *X*

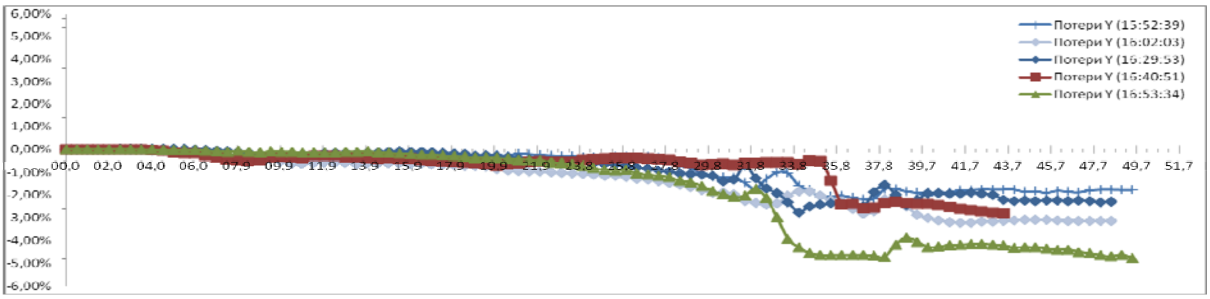

Fig. 8. The time dependence of the “parasitic” losses of energy of the tip panel deployment mechanism (% of the energy stored in the mechanism) when moving in *Y* direction

Рис. 8. Временная зависимость «паразитных» потерь энэргии механизма раскрытия концевой панели (% от энергии, запасенной в механизме) при движении в направлении *Y*

The obtained graphs are correct within the framework of the considered model up to the moment of time 29.8–30 seconds. At this point, the "locking" mechanisms of solar panels start functioning and after their operation the movement of panels practically ceases, and accordingly the movement of portals and carriages ceases to be independent and part of the energy goes to the SP fastening system. But from the point of view of GET this moment is already of no interest, because the deployment is completed.

From the graphs obtained it can be seen that the "parasitic" energy losses slightly exceed the value of 10 %. These losses are due to the fact that practically throughout the SP deployment the angle of the suspender deviation remains constant and is about 0.05º. This value can be reduced by increasing the "integral component" in the coefficients describing the operation of the PID controller. This reduces the stability of the entire WCS. The way to set the target function of the suspender deviation angle as 0.05º instead of 0º seems to be much simpler. Due to the wide possibilities for changing the algorithms of the WCS control system there are other ways to reduce the "parasitic" energy losses of the deployment mechanisms.

The motion range of the panels along the vertical in the experiments was less than 30 mm and did not actually affect the energy losses. Nevertheless, the inclusion of the WCS mechanism which ensures the compensation of the deviations in the weight component made it possible to reduce this value by more than three times.

Conclusion. An automated active weight-compensation system for deployment of solar cells of space vehicles was developed, created and tested.

The results of departmental tests showed that the weight compensation system with specified parameters described in this paper allows for ground-based tryout of the deployment of solar panels of all constructions, both currently existing and being developed for the future.

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